

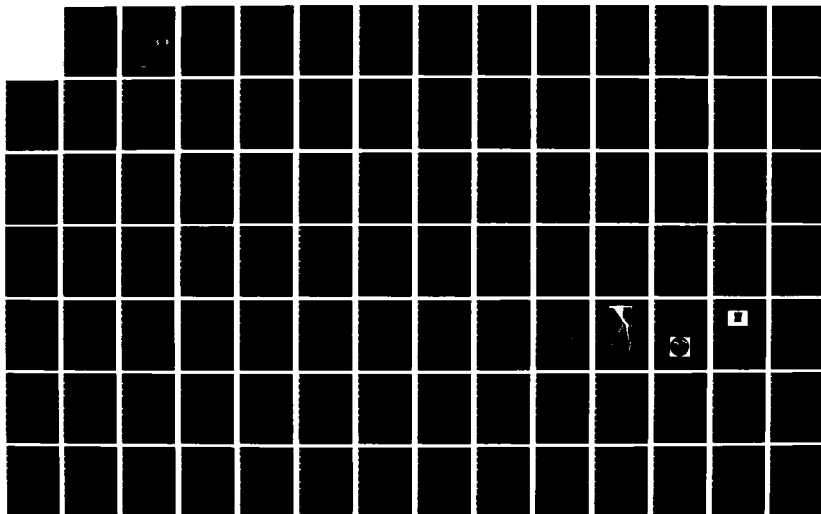
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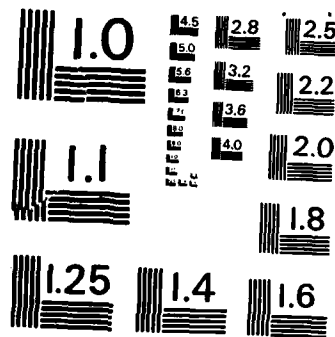
ELECTROSLAG PROCESSING FOR MARINE APPLICATION SUMMARY  
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Report EW-20-85

"ELECTROSLAG PROCESSING FOR  
MARINE APPLICATIONS"

Summary Report On A  
Workshop Held At:

~~United States Naval Academy~~  
~~Annapolis, Maryland 21402~~

5-6 March 1985.

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UNITED STATES NAVAL ACADEMY  
DIVISION OF  
ENGINEERING AND WEAPONS  
ANNAPOLIS, MARYLAND

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## FOREWORD

A one and a half day international workshop was held at the United States Naval Academy, Annapolis, Maryland, to discuss the status of electroslag technology and its potential for marine applications. Initially, a series of presentations were made to review the status of electroslag welding and casting in ferrous and nonferrous alloys. Following this introduction, current applications and trends for this technology were reviewed by the workshop's participants.

The final sessions consisted of a series of working group meetings where the key issues and current limitations preventing the expansion of this technology into marine applications were identified. A summary of the working group meetings were presented in a final plenary session. This document presents an overview of this workshop and its findings.

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## SUMMARY

## SUMMARY

↙ This document presents an overview of a one and one-half day, international workshop held at the United States Naval Academy, Annapolis, Maryland. The purpose of the workshop was to review and discuss the status of electrosag processing technology and to identify opportunities and directions for expanded application of electrosag processing technology in marine applications.

A series of presentations were made to review the status of electrosag welding and casting in ferrous and nonferrous alloys. Following this introduction, current applications and trends for this technology were reviewed by the workshop's participants. The final sessions consisted of a series of working group meetings where the key issues and opportunities for expansion of this technology into marine applications were identified.

← Cont'd p. 1  
In general, the workshop participants agreed that electrosag processing is a relatively mature technology which is used extensively in marine applications. Expanded application of this technology may be realized if technical progress is made in the following areas:

- Development of electrosag filler metals and procedures to take advantage of the improvements in high strength low alloy steel processing technology. Microalloyed steels continue to be developed with superior heat affected zone toughness at high heat inputs. Parallel developments in high heat input welding consumables and in-process control techniques should be accelerated.
- The capability to control grain size and attain mechanical properties equivalent to forged products should be developed and demonstrated for electrosag castings. Manufacturing procedures for steel components with acceptable mechanical properties and hydrogen levels should be developed. Grain size and impurity level control in non-ferrous alloys, particularly titanium alloys, should be pursued.
- A need, which is more generic than electrosag welding or processing, is the requirement for analytical tools to assess costs of alternative manufacturing processes, specifically welding processes. Process selection tradeoffs, such as fit up requirements, consumables, joint preparation, electrical intensity, etc., must be considered in a manageable form so that optimum process/application selections are made.

Details of the technical presentations and the working group recommendations are presented in the following sections of this document.

SESSION I  
ELECTROSLAG WELDING OF  
FERROUS ALLOYS

## Electroslag Welding of Pressure Vessel Steels

Robert H. Frost  
Jerald E. Jones  
David L. Olson

Department of Metallurgical Engineering  
Colorado School of Mines

### I. INTRODUCTION

Electroslag welding research at the Colorado School of Mines has been concerned with three major areas: process control, flux development, and the influence of electrochemical reactions on flux and weld metal compositions. A general description of the electroslag welding process, its control, and the properties of electroslag welds may be found in references 1 through 10. The first eight reference deal with the electroslag process in general and with process control and weld properties. References 9 and 10 deal with flux development and chemical control in the electroslag welding process.

The process control research was designed to provide a functional relation between process variables, a two dimensional model for unsteady heat transport in the parent plates, an energy balance for the process as a whole, and a set of nomograms in process variable space which can be used for process control. Flux development efforts were concerned with time dependent changes in flux composition, and with the development of oxide and fluoride based flux compositions which minimize alloy composition changes, tramp element pickup, and allow for deoxidation of the weld pool. The electrochemical experiments utilized a divided electrochemical cell to separately evaluate the influence of anodic and cathodic reactions on weld metal composition.

### II. PROCESS CONTROL

Process control research was aimed at the development of a functional relation between the process variables (current, potential, electrode velocity, and weld geometry); and at the development of heat transport and energy balance models for process control applications. Figure 1 represents a schematic of the electroslag welding process in which a consumable wire electrode is melted through a resistively heated flux bath to produce a single pass weld. Figure 2 shows that the welding current is proportional to the square root of the wire electrode velocity, and to the potential to the one third power:

$$I = W^{1/2} V^{1/3} \quad (1)$$

This functional relation makes it possible to develop an energy balance for process control.

The energy balance equates the power input (IV) to the various heat requirements:

$$IV = Q_p + Q_R + Q_W + Q_L + Q_T = Q_{total} \quad (2)$$

where:

- $Q_p$  = Heat into the parent plates
- $Q_R$  = Heat radiated from the slag surface
- $Q_W$  = Heat to melt the wire electrode
- $Q_L$  = Heat conducted to the weld pool
- $Q_T$  = Heat loss in the guide tube

A model for the heat input to the parent metal plates is obtained by solving the partial differential equation for unsteady heat conduction to obtain a solution which represents a moving strip heat source with a constant surface heat flux boundary condition at the flux bath/parent plate interface. The differential equation for unsteady heat flow is:

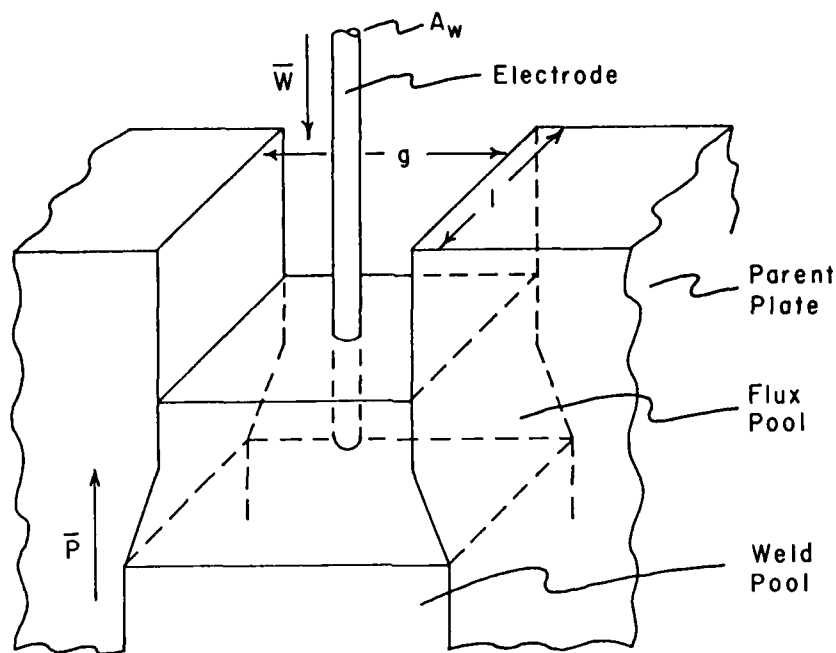


Figure 1 - Schematic of the electroslog welding process.

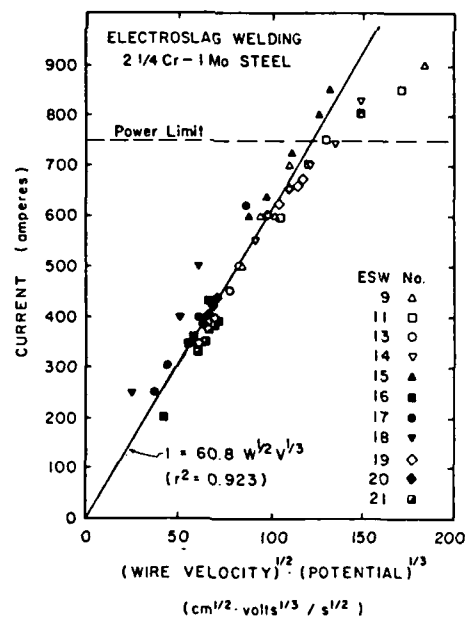


Figure 2 - Welding current as a function of electrode velocity and welding potential



$$\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} + \frac{\partial^2 T}{\partial Z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (3)$$

A solution for the constant surface heat flux boundary condition is given by Carslaw and Jaeger (11):

$$T - T_0 = \frac{2\alpha q}{\pi k U} \int_{U/2\alpha(X-b)}^{U/2\alpha(X+b)} e^{-U} K_0 \{ (UZ/2\alpha)^2 + U^2 \}^{1/2} dU \quad (4)$$

where:  $\alpha$  = Thermal diffusivity  
 $k$  = Thermal conductivity  
 $q$  = Surface heat flux (cal/cm<sup>2</sup>s)  
 $U$  = Weld pool velocity (cm/s)  
 $b$  = Half depth of the flux pool  
 $K_0$  = Modified Bessel Function of the Second Kind

For process control purposes it is assumed that the heat input to the parent plates will be sufficient to raise the parent plate surface to the melting point at the mid-depth of the flux pool. This solution can be simplified by setting the surface temperature of the parent plate at the midpoint of the flux pool ( $Z = 0$ ,  $X = 0$ ) equal the melting point ( $T_m$ ):

$$T_m - T_0 = q/\pi k \{ 2b \exp(Ub/2\alpha) [K_0(Ub/2\alpha) + K_1(Ub/2\alpha)] - 4\alpha/U \} \quad (5)$$

An expression for the total rate of heat input to the weld required to heat up the parent plates can be obtained by solving equation 5 for the heat flux and multiplying by the perimeter area wetted by the flux bath:

$$Q_p = \frac{(1 + g)d\pi k(T_m - T_0)}{b \exp(Ub/2\alpha) [K_0(Ub/2\alpha) + K_1(Ub/2\alpha)] - 2\alpha/U} \quad (6)$$

where:  $d$  = flux pool depth

The rate of heat loss by radiation from the surface of the flux bath is expressed by the Stephen-Boltzman law:

$$Q_R = 1g\epsilon\sigma T_g^4 \quad (7)$$

where:  $\epsilon$  = flux emissivity  
 $\sigma$  = radiation constant

The heat required to melt the electrode includes the sensible heat to raise the electrode to the liquidus and the heat of fusion:

$$Q_w = \pi r_w^2 W (\rho C_p [T_m - T_0] + \rho \Delta H_f) \quad (8)$$

where:  $\rho$  = density of the alloy  
 $C_p$  = specific heat  
 $r_w$  = radius of the electrode

The rate of heat conduction from the flux bath to the weld pool is a function of the boundary heat transport coefficient ( $h$ ) and the temperature difference between the flux and the metal pool:

$$Q_L = 1gh(T_g - T_m) \quad (9)$$

where:  $T_g$  = temperature of the flux bath  
 $T_m$  = liquidus temperature of the alloy

The resistive heat loss in the guide tube is given by Ohm's Law:

$$Q_T = I^2 [\bar{\rho} L_t / A_t] \quad (10)$$

where:  $\bar{\rho}$  = average resistivity ( $\Omega\text{cm}$ )  
 $l_t$  = length of the guide tube  
 $A_t$  = guide tube cross sectional area.

The power input required to produce a successful electroslog weld can be found by substituting the expressions for the various heat requirements into the overall heat balance. This expression can then be used to find the minimum welding potential for a successful weld as a function of the welding current. Figure 3 shows plots of the minimum welding potential for electroslog welds of 1.75 inch (44.5 mm), 4 inch (101.6mm), and 6 inch (152.4mm) thick 2 1/4 Cr - 1 Mo steel plate.

The process space within which adequate welds can be produced is bounded by four process space boundaries. The lower boundary represents the threshold voltage for parent plate penetration as determined based on the energy balance above. The right hand and upper boundaries represent the maximum power and maximum voltage outputs of the power supply, and the left hand boundary represents a minimum electrode velocity below which the electrode melts off above the flux bath and the process becomes discontinuous.

Figure 4 compares the prediction of the energy balance with experimental data for 4 inch (101.6 mm) plate welds. The solid data points represent welds which penetrated or fused to the parent plate, and the open data points represent welds in which lack of fusion or non-penetration defects were observed. These data and similar data for 1.75 in. (44.5 mm) and 6 in. (152.4 mm) thick welds show that the threshold potential predicted by the energy balance provides an excellent representation of the energy input required for penetration of the parent plate.

The energy balance can be used to analyze the relative magnitudes of the various heat requirements as a function of the welding current or electrode velocity. Figure 5 shows a plot of the % heat requirements as a function of the welding current. The fraction of the heat absorbed by the parent plates decreases dramatically with increasing current and weld velocity. At a low current the weld is quasistatic, and the parent plates conduct away around 78% of the heat. At a high current (high welding velocity) the fraction of the total heat absorbed by the parent plates decreases to about 50%, and the fraction of the heat used to melt the wire electrode increases to about 38%. Thus, the efficiency as expressed by the fraction of heat used to melt the electrode increases with increasing current.

The thermal history of the heat affected zone is a major factor in determining weld quality and the need for a re-austenitizing post weld heat treatment. The energy balance can be used to determine the total heat absorbed per unit area of the parent plate surface. Figure 6 plots the total heat input ( $\text{kcal/cm}^2$ ) as a function of the welding current. This shows that the behavior of electroslog welds is the opposite of that observed for arc welding processes. In arc welding an increase in the current at a constant weld velocity causes an increase in the heat input per unit length of weld. In electroslog welding an increase in the welding current is coupled with increases in electrode and weld velocities, and a decrease in the total heat input per unit parent plate surface area. Figure 6 shows that the heat input falls from 60 to about 5  $\text{kcal/cm}^2$  as the current is increased from 200 to 1,000 amperes.

The two dimensional model of heat transport in the parent plates can be used to investigate the influence of process variables on the temperature distribution in the parent plate and the thermal history of the heat affected zone. The solution to the partial differential equation for unsteady heat transport gives the temperature  $T(x,z)$  in the parent plate as a function of the location with respect to the flux and metal pools, the heat fluxes, the weld velocity, and the thermal properties of the steel:

$$T(x,z) = \frac{q_a}{\pi k a} \int_a^b \exp[U/2\alpha(x-x')] K_0 \{U/2\alpha[(x-x')^2 + Z^2]^{1/2}\} dx' + \frac{q_m}{\pi k b} \int_b^c \exp[U/2\alpha(x-x')] K_0 \{U/2\alpha[(x-x')^2 + Z^2]^{1/2}\} dx' \quad (11)$$

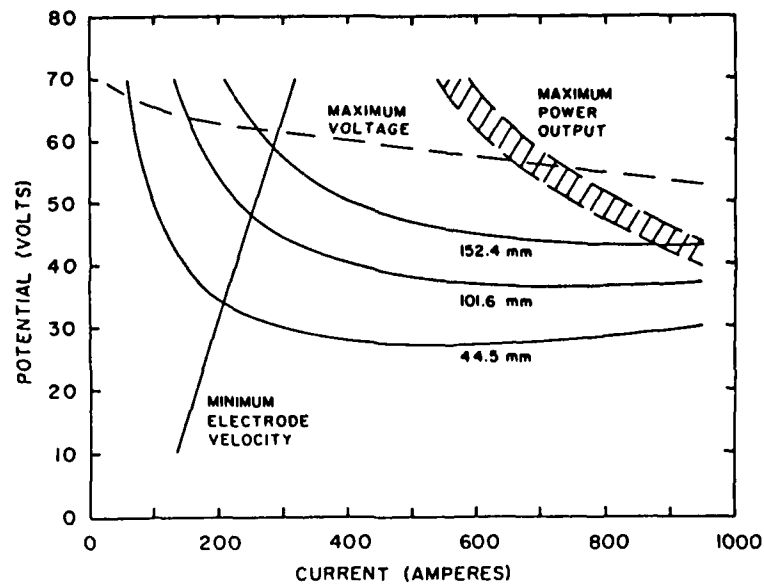


Figure 3 - Process operating space in current-potential coordinates. The lower boundaries represent the threshold potential required for fusion of the parent plates.

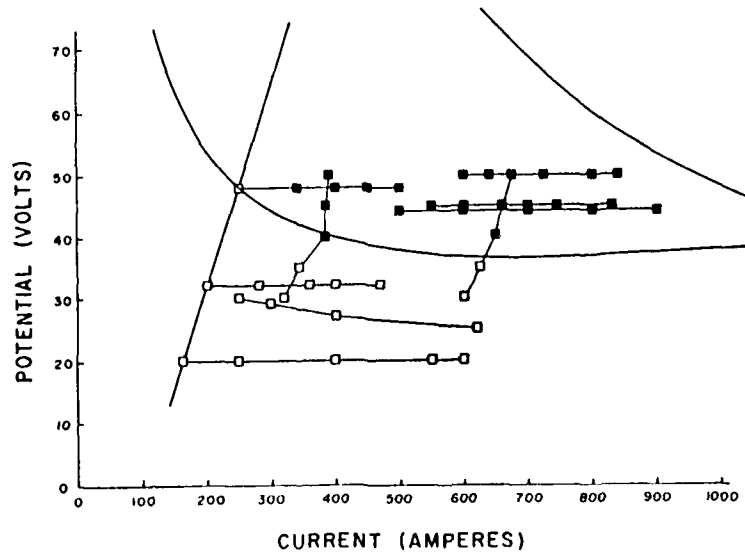


Figure 4 - Process operating space for 4.0 in. (101.6 mm) thick electroslog plate welds. Closed data points indicate parent plate fusion and open data points indicate incomplete fusion.

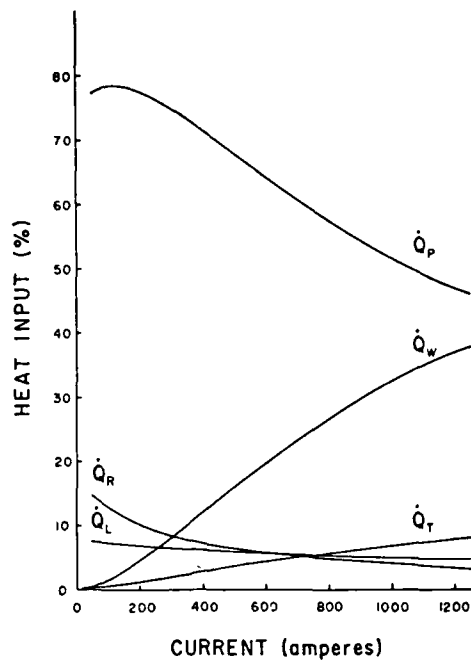


Figure 5 - Percentage heat input requirements as a function of welding current for an electroslag weld of 4 in. (101.6mm) thick steel plate.

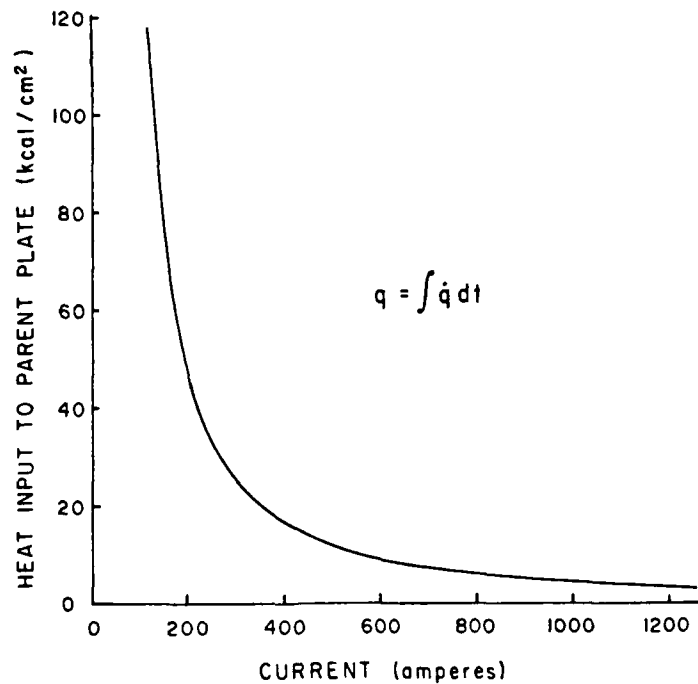


Figure 6 - Total heat input per cm² of parent plate surface area for an electroslag weld of 4 in. (101.6 mm) steel plate.

Figures 7, 8, and 9 show plots of the isotherms in the parent plates of 4 inch thick welds produced at currents of 300, 500, and 700 amperes. The ordinate shows the location with respect to the flux and metal pools with the slag/metal interface at zero. The abscissa represents the distance from the fusion line along the z-axis. The extent of reaustenization in the heat affected zone is controlled by the location of the 750°C isotherm, which is the A<sub>1</sub> temperature for 2 1/4 Cr - 1 Mo steel. The portions of the heat affected zone which pass within the 750°C isotherm and undergo reaustenization are indicated by shading.

An alternate method of illustrating the temperature distribution is provided by an isometric plot of the temperatures along planes parallel to and normal to the parent plate surface. Figures 10, 11, and 12 show isometric plots of the temperature distribution in 1.75 inch (44.5mm) thick steel plate at welding currents of 300, 600, and 900 amperes. These plots show that as the welding current and weld velocity increase the thermal gradients become steeper, and the extent of the heat affected zone becomes more limited.

The thermal history of the heat affected zone is important, because the rate of cooling below the eutectoid temperature strongly influences austenite decomposition which controls the microstructure and mechanical properties. For 2 1/4 Cr - 1 Mo steel a cooling rate greater than 30°C per minute results in the formation of acicular ferrite with good Charpy impact toughness. A cooling rate slower than 30°C per minute produces allotriomorphic grain boundary ferrite, and causes a decrease in toughness.

Figures 13 and 14 show temperature versus time plots for 4 inch (101.6mm) thick electroslog welds produced at currents of 500 and 700 amperes. The time is determined by dividing the distance along the weld (x axis) by the weld velocity. Zero on the time axis corresponds to the passage of the slag/metal interface. The temperature profiles are drawn for the fusion line and for distances of 1, 2, 3, 4, and 5 cm. from the parent plate surface. The horizontal line is drawn at the eutectoid temperature of 750°C. Figure 13 shows that the first 4 cm. of the heat affected zone are reaustenitized at a welding current of 500 amperes, and Figure 14 shows that reaustenization reaches to a depth of only 2.5 cm. at a current of 700 amperes.

Table I summarizes the influence of welding current on the thermal history in the heat affected zone. At a distance of 20 mm from the parent plate surface, an increase in the welding current from 300 to 700 amperes causes the peak temperature to fall from 1160°C to 870°C. The time above the A<sub>1</sub> temperature during which austenite grain growth can occur drops from 67.5 minutes to 5.8 minutes, and the cooling rate below the eutectoid increases from 4.5°C/min. to 40.0°C/min. Thus, a welding current of 700 amperes provides a cooling rate sufficiently high to avoid the formation of proeutectoid ferrite (>30°C/min.). A welding current of 500 amperes provides too low a cooling rate and allows the formation of proeutectic grain boundary ferrite which decreases weld metal and heat affected zone toughness.

**TABLE I - Thermal History of the Heat Affected Zone 20mm from the Parent Plate Surface of 4 inch Thick Electroslog Plate Welds**

Current (amperes)	300	500	700
Peak Temperature (°C)	1160	1023	870
Time above A <sub>1</sub> (min)	67.5	15.5	5.8
Cooling Rate <sup>1</sup> (°C/min) at 700°C	4.5	18.0	40.0

The research reported above provides the basis for two major conclusions on process control and heat transport in the electroslog welding process:

1. A process control model based on an energy balance is valid for D.C. electroslog welds of up to 6 inch thick plate.
2. Heat input to the parent metal plates decreases with increasing current. This suggests the use of high power-high velocity welds to minimize the extent of the heat affected zone and to refine the fusion zone microstructure.

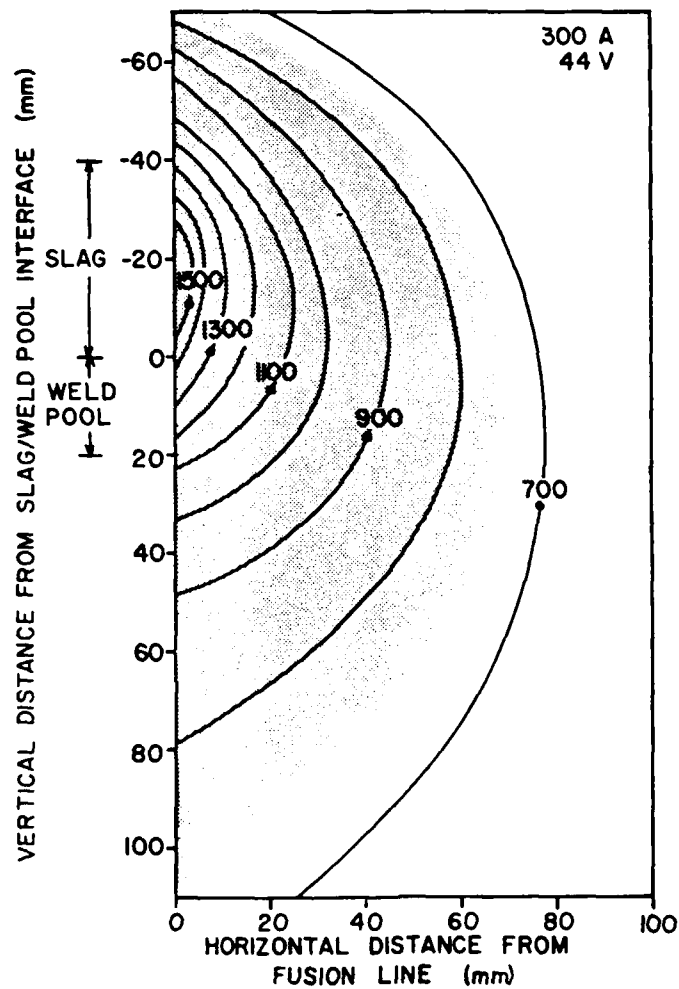


Figure 7 - Temperature contours in the parent plate of a 4 in. (101.6 mm) thick electroslag weld produced at a welding current of 300 amperes.

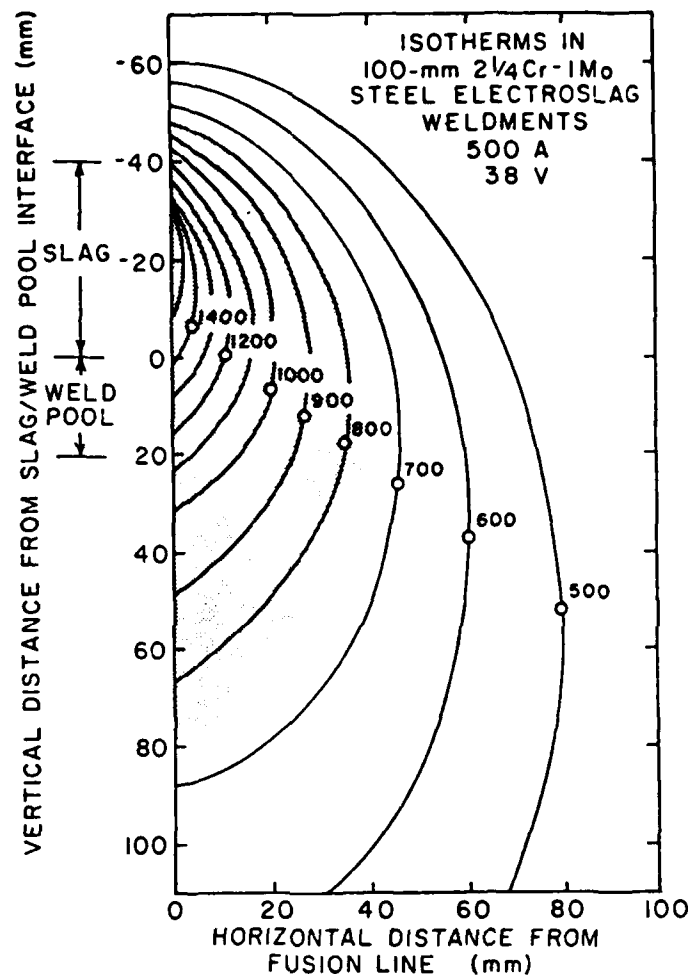


Figure 8 - Temperature contours in the parent plate of a 4 in. (101.6 mm) thick electrosag weld produced at a welding current of 500 amperes.

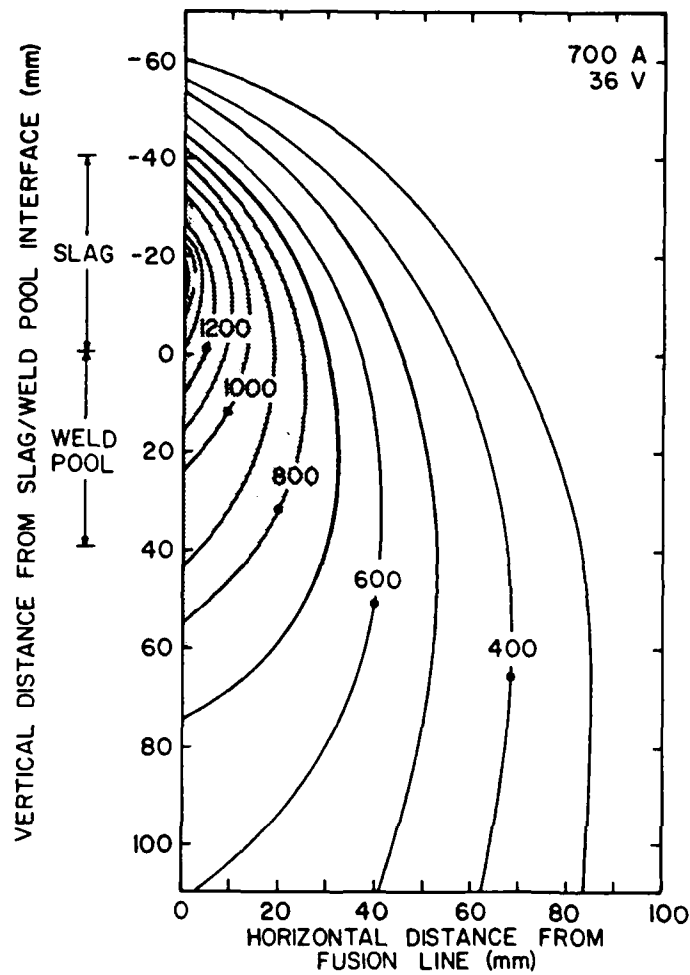


Figure 9 - Temperature contours in the parent plate of a 4 in. (101.6 mm) thick electroslag weld produced at a welding current of 700 amperes.



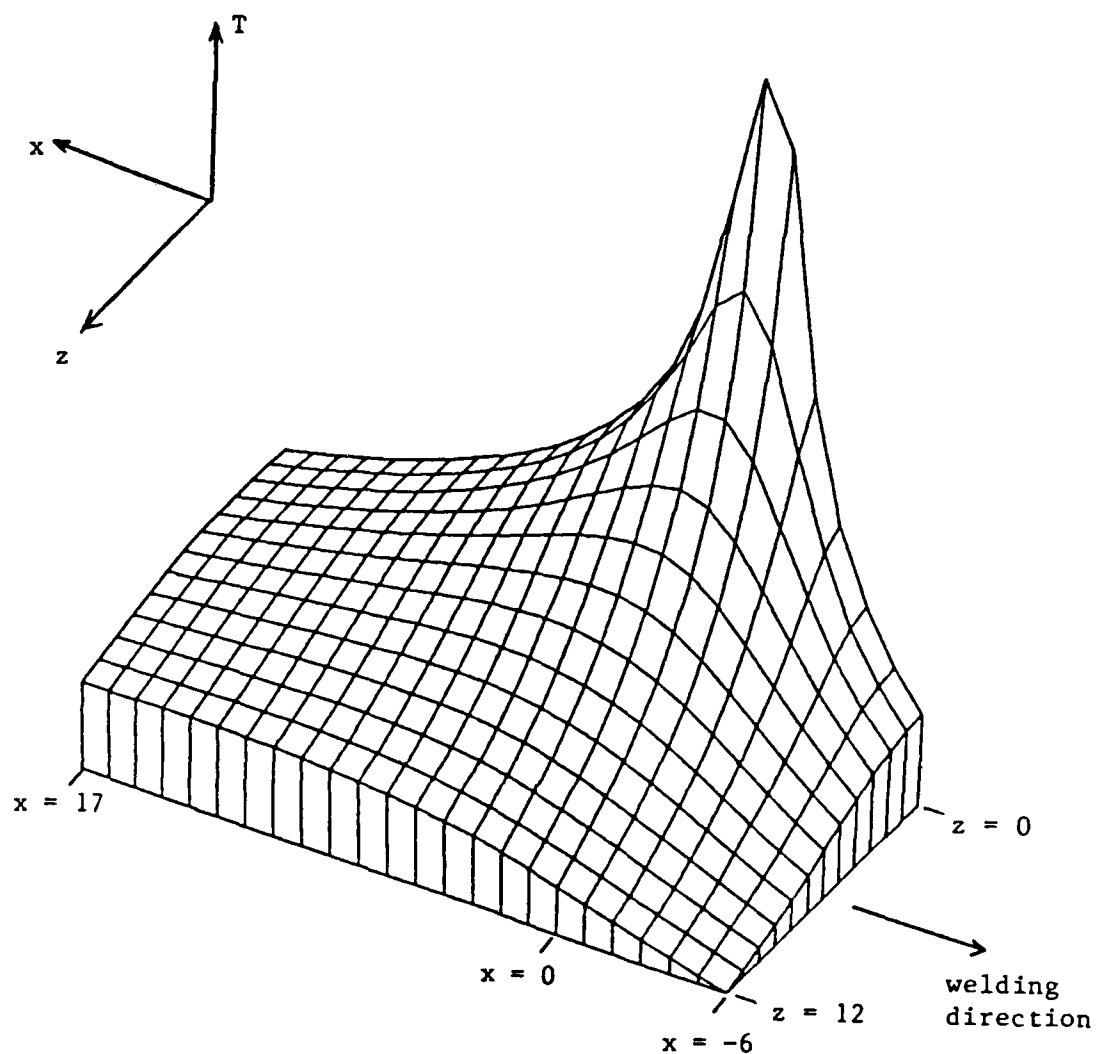


Figure 10 - Three dimensional plot of the parent plate temperatures in a 1.75 in. (44.5 mm) thick electroslog weld produced at a welding current of 300 amperes.

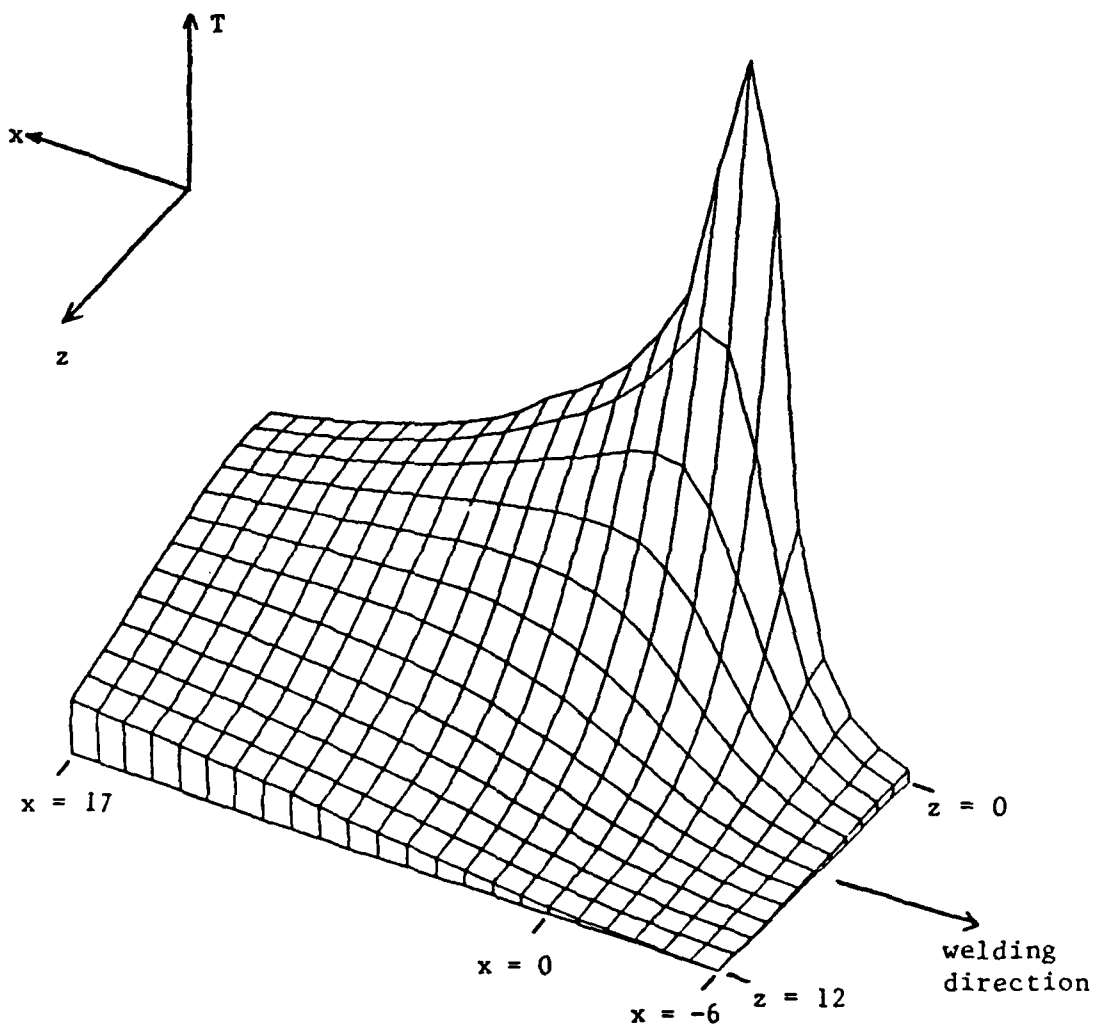


Figure 11 - Three dimensional plot of the parent plate temperatures in a 1.75 in. (44.5 mm) thick electroslog weld produced at a welding current of 600 amperes.

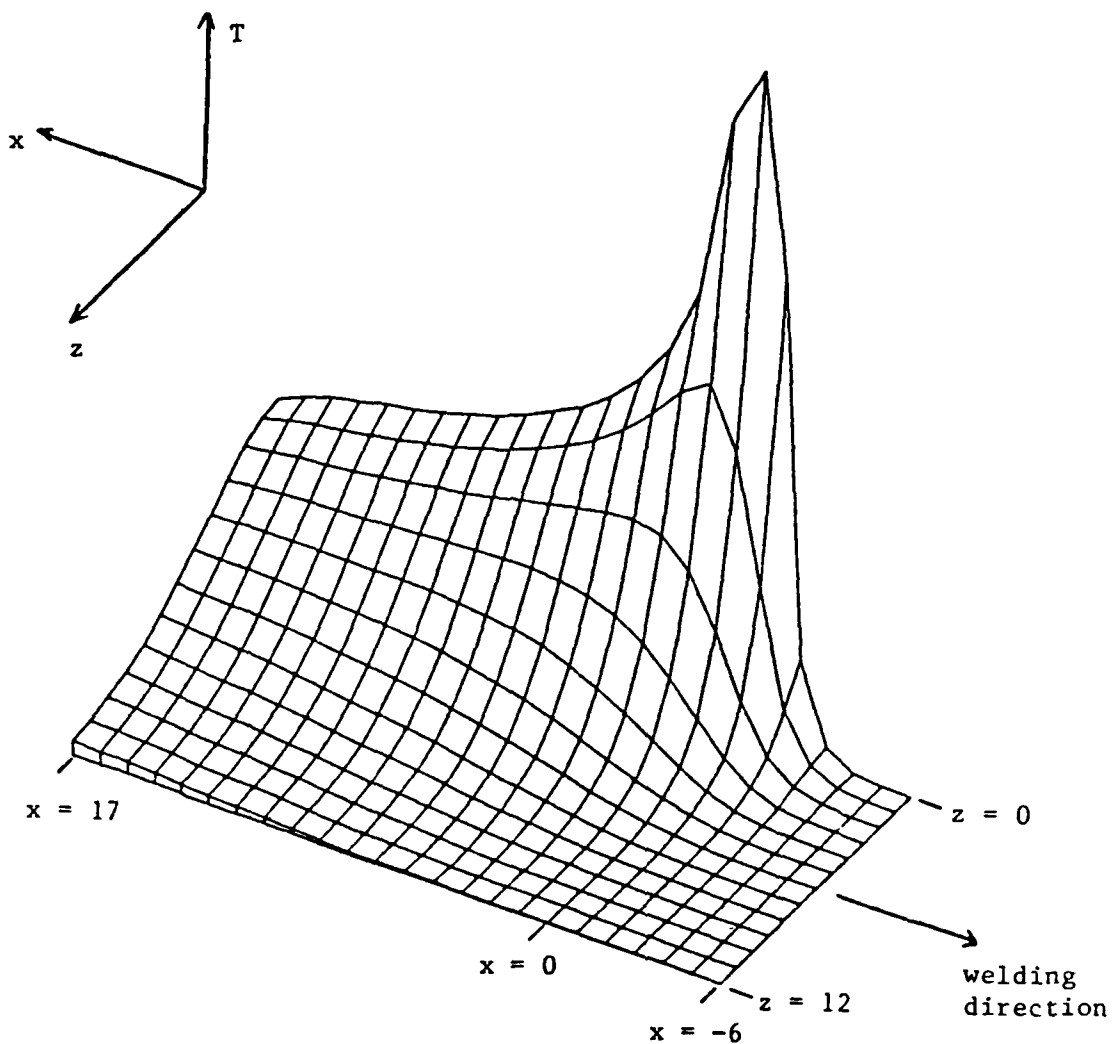


Figure 12 - Three dimensional plot of the parent plate temperatures in a 1.75 in. (44.5 mm) thick electroslog weld produced at a welding current of 900 amperes.

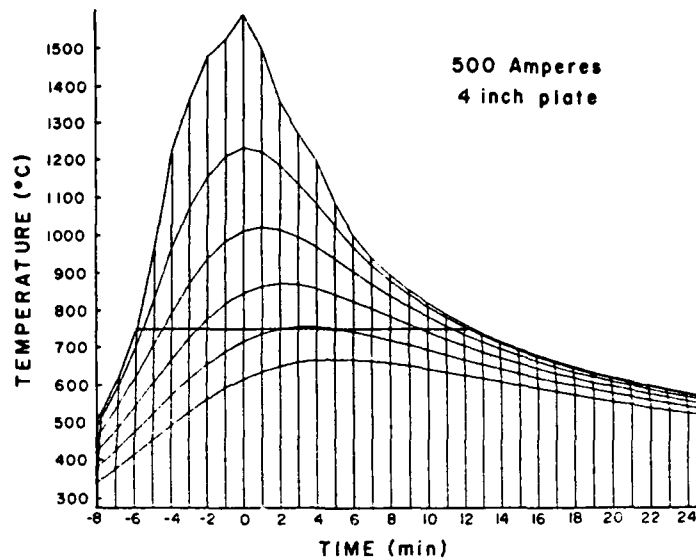


Figure 13 - Calculated time-temperature profiles at 10 mm increments of depth into the parent plate of a 4 in. (101.6 mm) thick electro-slag weld produced at a current of 500 amperes.

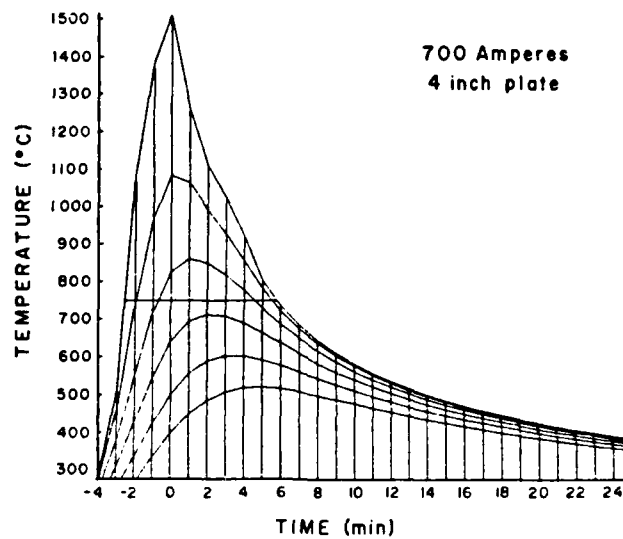


Figure 14 - Calculated time-temperature profiles at 10 mm increments of depth into the parent plate of a 4 in. (101.6 mm) thick electro-slag weld produced at a current of 700 amperes.

### III. ELECTROSLAG FLUX DEVELOPMENT

Electroslag flux development studies were carried out to evaluate: (1) time dependent flux and metal composition changes in oxide and fluoride based fluxes, (2) the influence of alloy and flux additions on weld metal composition, and (3) flux and weld pool deoxidation for oxide and fluoride based fluxes. Electroslag welds were produced in a water cooled crucible to prevent dillution, and the composition of the weld metal deposit was determined at distances of 1, 2, 4, 8, and 12 inches from the starting tab.

Figure 15 shows the changes in the silicon, chromium, manganese, and oxygen concentrations as a function of distance from the starting tab for a 2 1/4 Cr - 1 Mo steel weld produced using a commercial oxide based flux. The high silica content of the flux causes silicon to be picked up by the weld metal in the initial portion of the weld. This indicates that the silicon activity in the flux is higher than that in the weld metal. After about 8 inches of weld the silicon concentration approaches steady state with neither pickup or losses of silicon by the weld metal.

Chromium shows an initial oxidation loss from the weld metal to the flux during the first 8 inches of weld. This is caused by the absence of chromium oxide in the initial flux composition. After about 8 inches of weld the chromium concentration in the flux saturates and the chromium content approaches steady state in both the flux and weld metal. Manganese shows a continuous oxidation loss because the manganese activity in the flux is lower than that in the weld metal. The scale for the oxygen concentration is given on the right hand side of the figure. Oxygen shows a concentration of about 200 ppm over the whole length of the weld. This represents a constant oxygen pickup of about 130 ppm from the 70 ppm present in the wire electrode. This experiment shows that alloy and tramp element concentrations are not constant, that considerable startup transients are observed, and that the concentrations of some of the alloy elements approach steady state after several inches of weld.

Figures 16 through 19 compare the concentration changes for chromium, manganese, silicon, and the oxygen content as functions of distance along the weld for a commercial oxide based flux and a fluoride flux consisting of pure calcium fluoride. Figure 16 shows that the chromium concentration approaches neutrality (no pickup or loss) when an oxide based flux is used; however, chromium exhibits a continuous oxidation loss with a fluoride flux. This loss may be caused by the formation of volatile chromium fluorides. Figure 17 shows the opposite behavior for manganese. The manganese concentration approaches steady state when using a fluoride based flux, but continuous manganese losses are observed with the oxide flux. Figure 18 contrasts the silicon pickup observed with the high silica oxide based flux with the approximate steady silicon concentration observed for the fluoride based flux. Figure 19 shows the oxygen content as a function of distance from the starting tab. The oxide based flux provides a constant pickup of about 130 ppm to a level of around 200 ppm. The fluoride flux provides neither oxygen pickup nor deoxidation.

Figure 20 shows the influence of a 5%  $\text{Cr}_2\text{O}_3$  addition to the flux on weld metal chromium content for oxide and fluoride fluxes. In both cases the excess chromium in the flux causes an initial chromium pickup by the weld metal. With the oxide flux the chromium concentration approaches neutrality with increasing distance from the starting tab. With the fluoride flux the chromium concentration goes below neutrality to a position of a continuous chromium loss. The chromium oxide addition shows that weld metal composition can definitely be modified by flux additions. If alloy modifications are necessary, is preferable to make flux additions than to increase the alloy content of the electrode.

The flux chemistry experiments provide the basis for several conclusions:

1. Oxygen pickup and oxidation losses of alloy elements remain a problem for D.C. electroslag welding with oxide based fluxes.
2. Fluoride based fluxes minimize oxygen pickup and alloy oxidation losses for D.C. electroslag welding.
3. Deoxidation of oxide or fluoride based fluxes is impractical for DC electroslag welding processes.

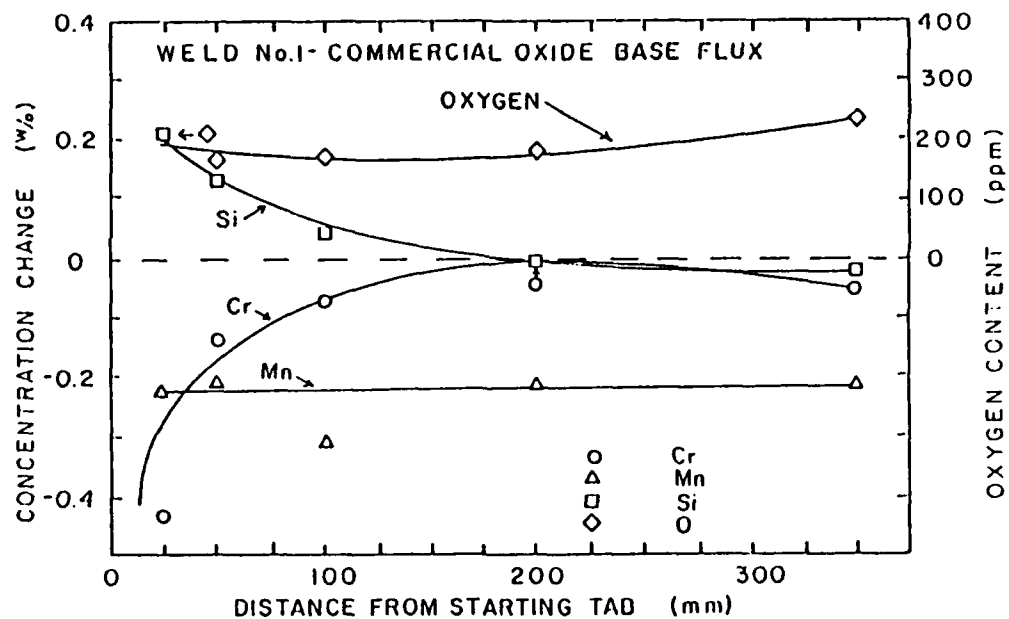


Figure 15 - Composition change as a function of distance from the starting tab for 2 1/4 Cr - 1 Mo welds produced using a commercial oxide based flux.

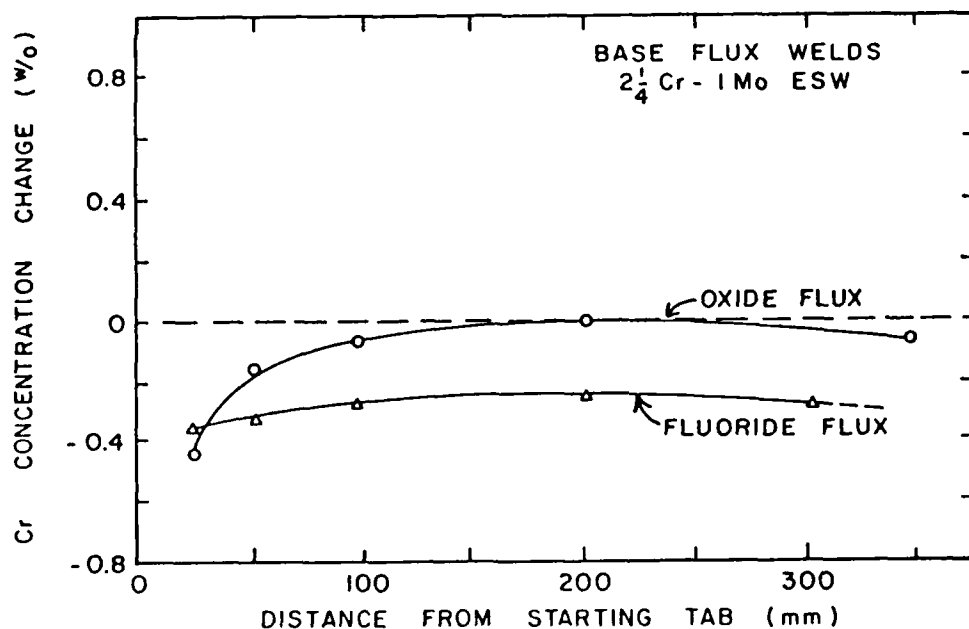


Figure 16 - Chromium composition change as a function of distance from the starting tab for electroslog welds produced using oxide and fluoride based fluxes.

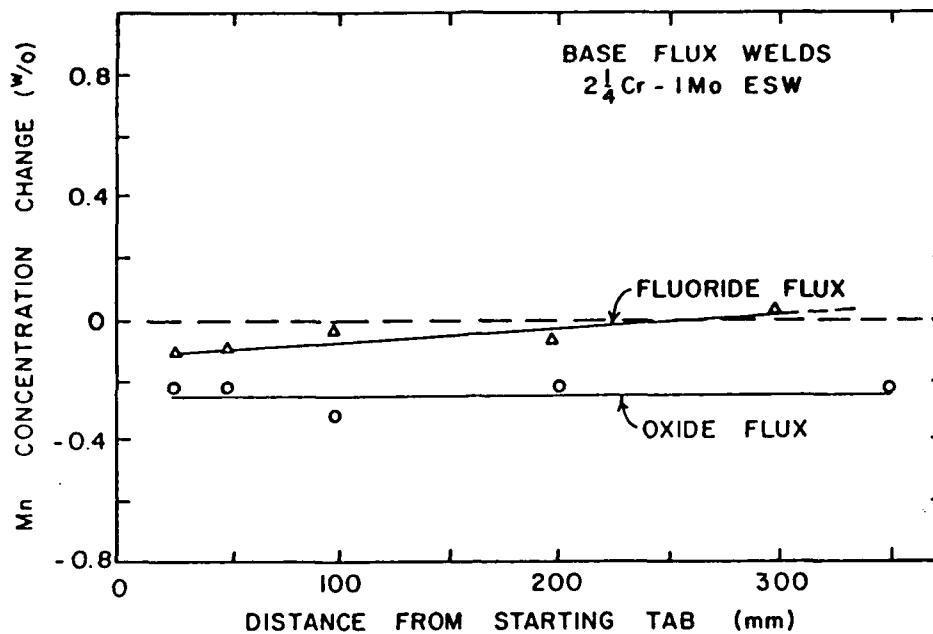


Figure 17 - Manganese composition change as a function of distance from the starting tab for electroslog welds produced using oxide and fluoride based fluxes.

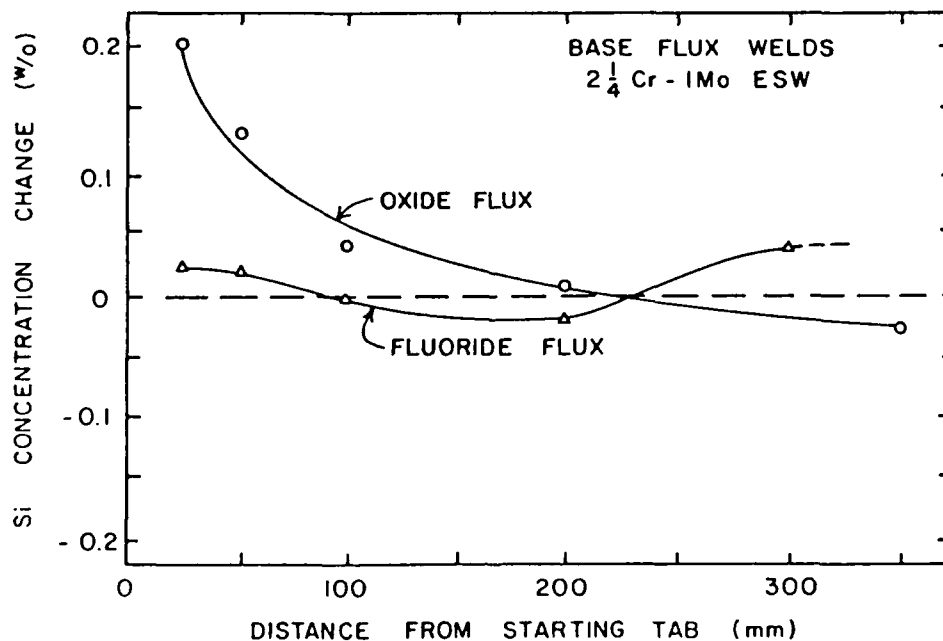


Figure 18 - Silicon composition change as a function of distance from the starting tab for electroslog welds produced using oxide and fluoride based fluxes.

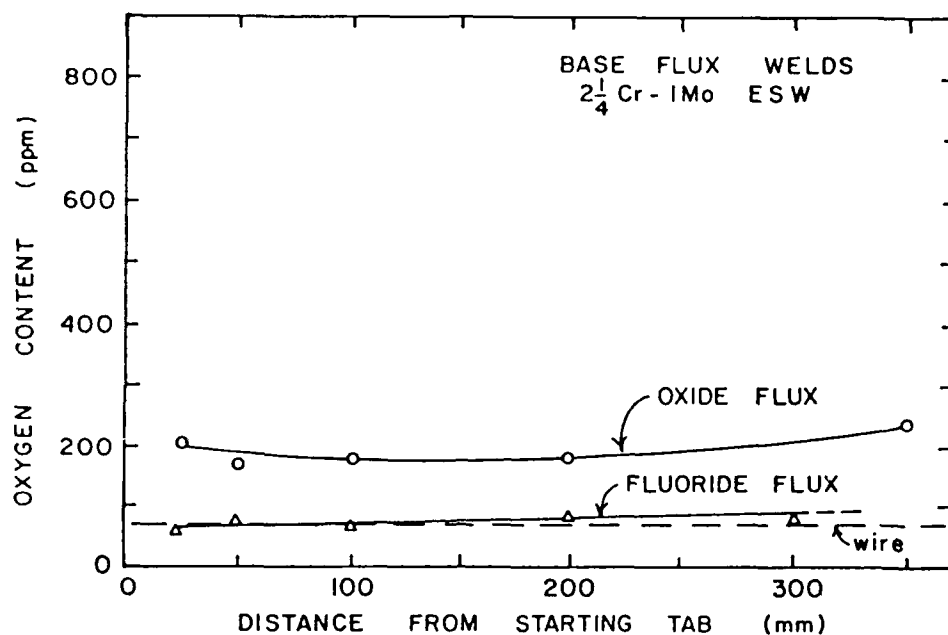


Figure 19 - Oxygen content as a function of distance from the starting tab for electroslag welds produced using oxide and fluoride based fluxes.

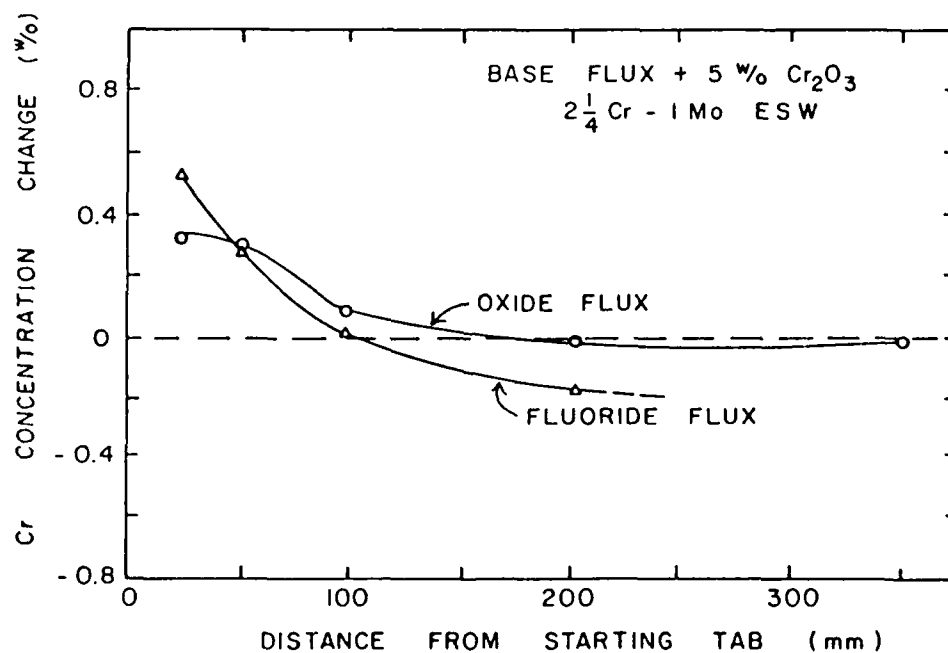


Figure 20 - Chromium concentration change as a function of distance from the starting tab for electroslag welds produced using oxide and fluoride based fluxes with a 5%  $\text{Cr}_2\text{O}_3$  addition.



#### IV. ELECTROCHEMISTRY

Electrochemical experiments were designed to evaluate the influence of electrochemical reactions caused by the D.C. current on the weld metal composition. The electrochemical reactions involve alloy element oxidation losses and the pickup of oxygen and metallic tramp elements from the flux. Figure 21 shows an electrochemical schematic of the reverse polarity (electrode positive) D.C. electroslag welding process. The reactions at the anode include: the oxidation of iron and alloy elements, the discharge of oxygen anions in the flux, and pickup of oxygen by the metal. The reactions at the cathode include: reduction of iron and alloy elements from the flux, the reduction of metallic tramp elements such as aluminum from the flux, and the refining of non-metallic tramp elements such as oxygen and sulfur.

The electrochemical experiments utilized a divided electrochemical cell to separate the products of the anodic and cathodic reactions. This is illustrated in Figure 22. The cell consisted of a 2 1/4 Cr - 1 Mo steel pipe on a base plate of the same alloy, and separation of the molten products was provided by a water cooled divider bar. The two electrodes consisted of a moving wire and a static plate. The difference in electrode surface areas provided a variation in the experimental current density. The flux was pre-melted in a separate welding experiment and teemed into the experimental crucible to start the experiment. After the experiment the buttons were retrieved from both sides of the cell and analyzed to evaluate the extents of the separate anodic and cathodic reactions. The initial experiments utilized a  $\text{CaF}_2$  - 10%  $\text{Al}_2\text{O}_3$  flux, and later experiments utilized a  $\text{CaF}_2$  flux with various MnO additions to investigate the influence of alloy element activity in the flux on the extents of electrochemical reactions.

Figures 23 through 27 show the experimental results plotted in terms of the change in alloy or tramp element concentrations. Figure 23 shows an anodic pickup of oxygen to levels as high as 400 ppm, and the cathodic pickup of aluminum to levels as high as 0.4%. The composition changes for oxygen at the cathode or aluminum at the anode are small. Figures 24 and 25 show oxidation losses of chromium, manganese, and silicon at the anode, and a smaller pickup of these elements by reduction from the flux at the cathode. The behavior of molybdenum shown in Figure 25 is the inverse of what would be expected from a metal. This apparent reversed behavior is the result of iron movement as will be demonstrated below. The results for phosphorus and sulfur in Figure 26 show refining at both the anode and cathode, and the results for carbon and nitrogen in Figure 27 show refining at the cathode and a small amount of pickup at the anode.

The apparent reversed behavior shown by molybdenum requires a more refined model to account for composition changes caused by the movement of iron across the cell. The current efficiency (E) for a particular electrochemical reaction may be defined as the ratio of the coulombs of charge involved in the reaction to the total coulombs of charge passed:

$$E = Q_r / Q_t \quad (12)$$

The coulombs of charge transferred by the reaction can be determined from chemical analysis:

$$E = \frac{(C_e W - C_b B)(n/M)F}{Q_t} \quad (13)$$

where:

- $C_e$  = concentration in the electrode
- $C_b$  = concentration in the button
- $W$  = weight of electrode melted
- $B$  = weight of recovered button
- $n$  = valence change
- $M$  = atomic weight of reacting species
- $F$  = faraday constant

For actual electroslag welds the weight of electrode melted is approximately equal to the weight of weld metal recovered, and Equation 13 can be modified as follows:

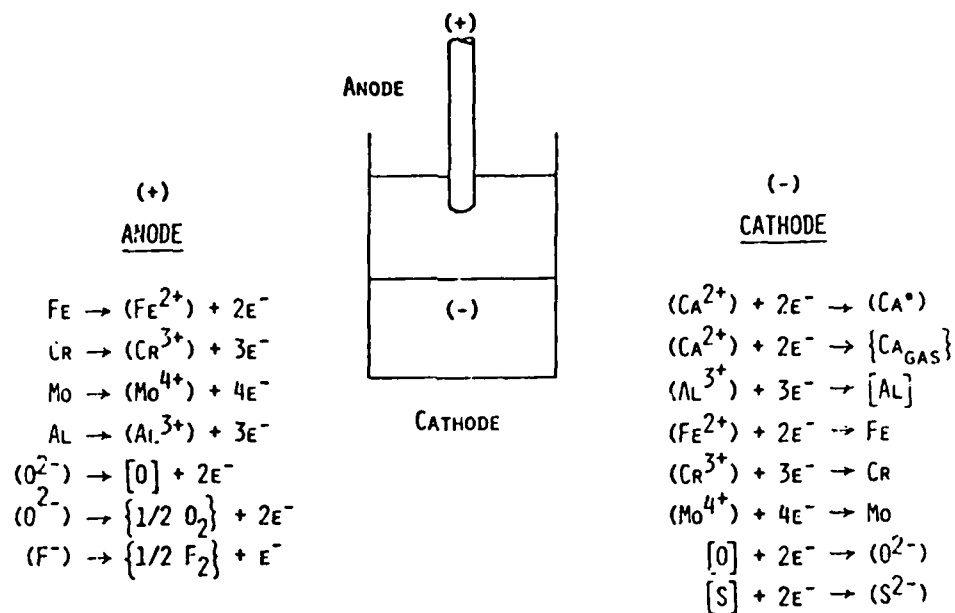


Figure 21 - Schematic illustration of possible electrochemical reactions in a reverse polarity D.C. electroslag Weld.

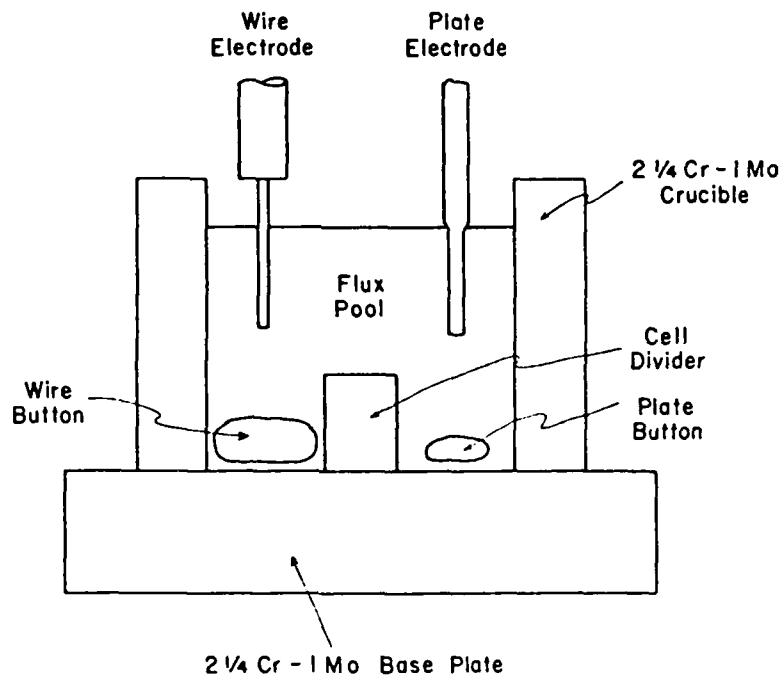


Figure 22 - Schematic of divided electrochemical cell used to separate the molten products from the anodic and cathodic electrochemical reactions.

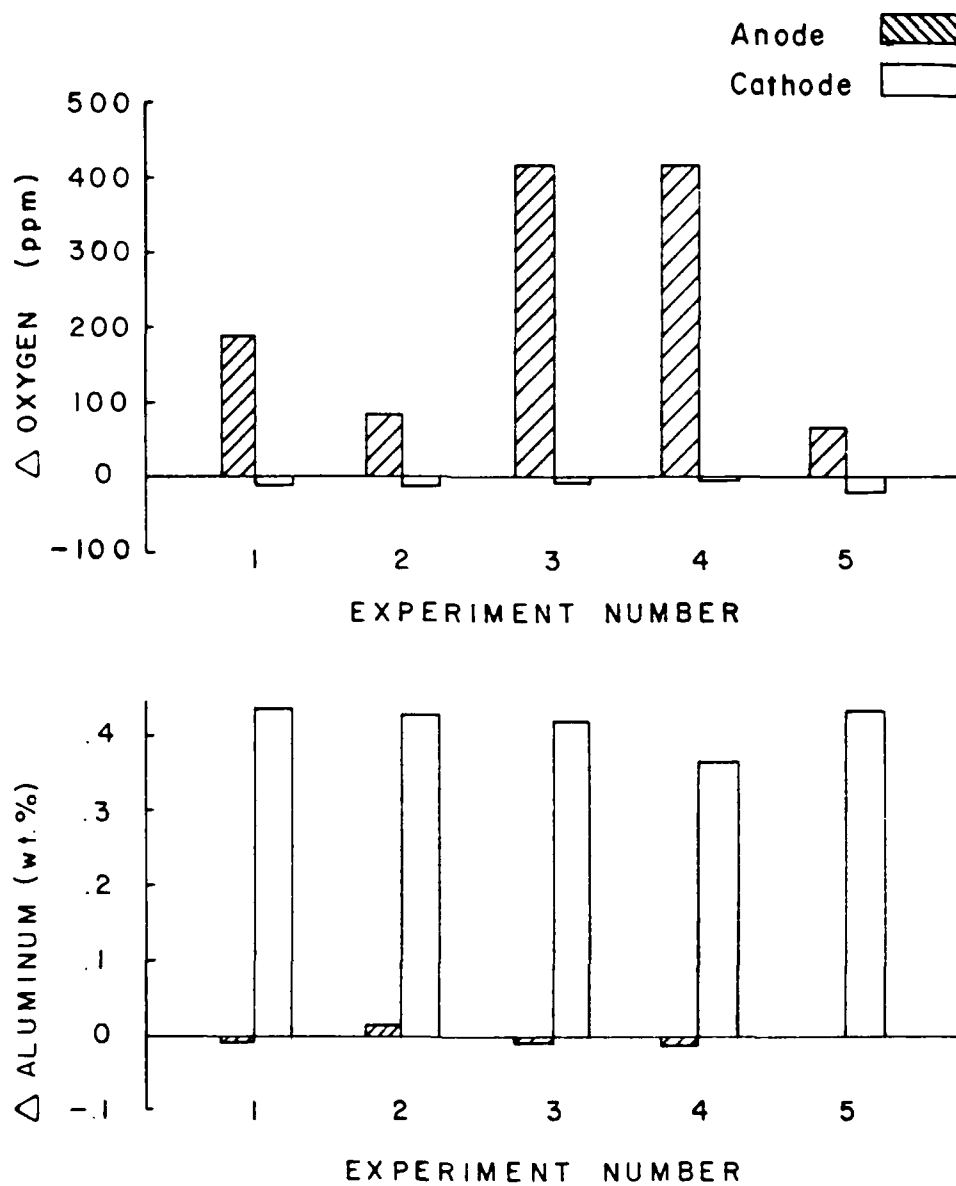


Figure 23 - Concentration changes for oxygen and aluminum at the anode and cathode of the divided electrochemical cell.

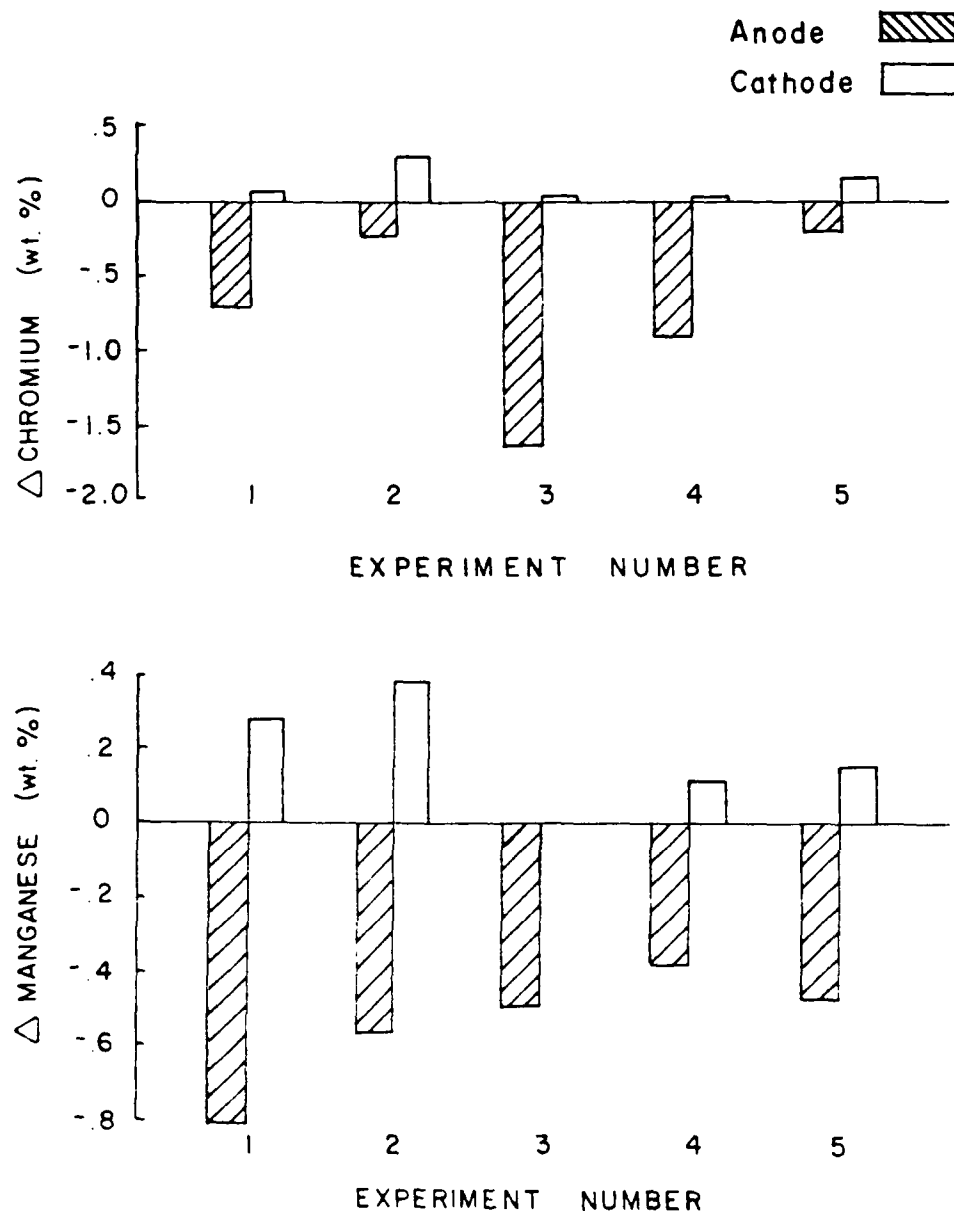


Figure 24 - Concentration changes for chromium and manganese at the anode and cathode of the divided electrochemical cell.

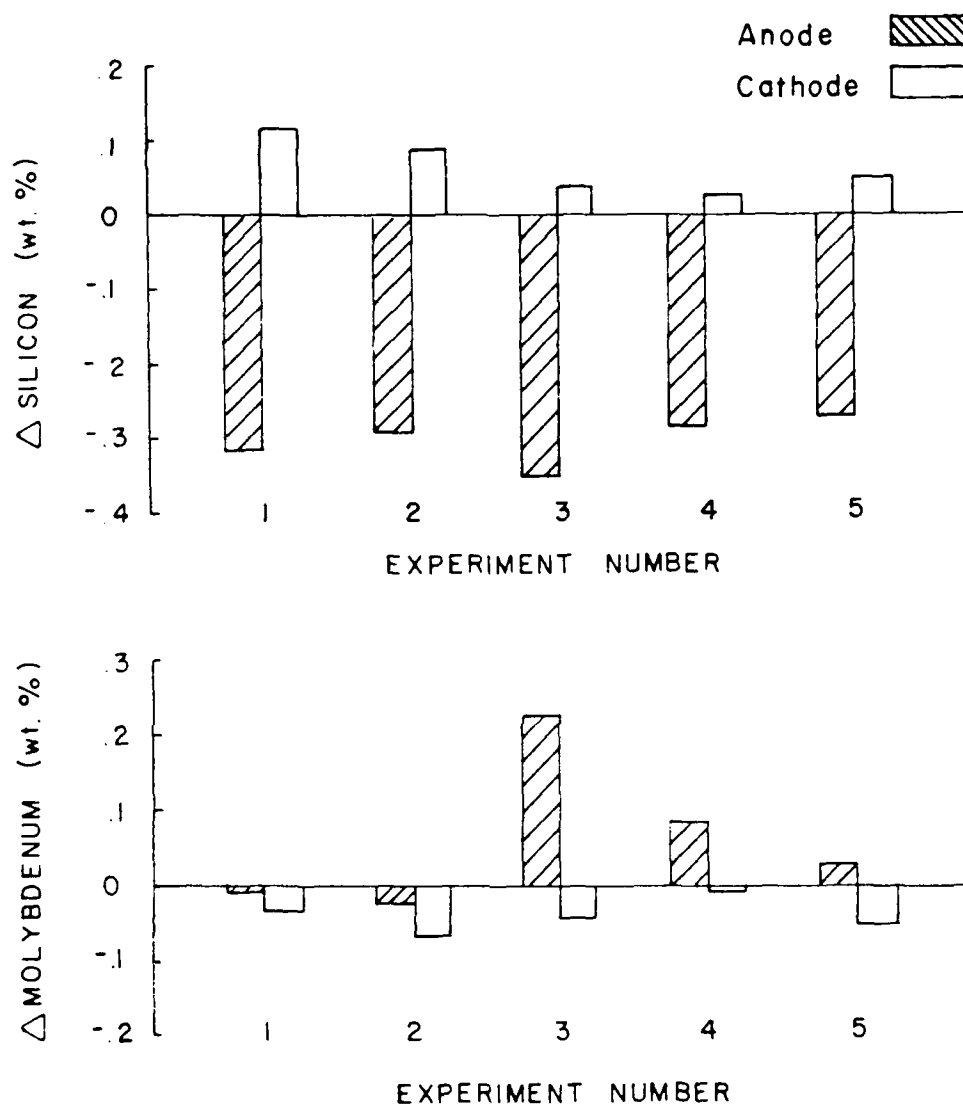


Figure 25 - Concentration changes for silicon and molybdenum at the anode and cathode of the divided electrochemical cell.

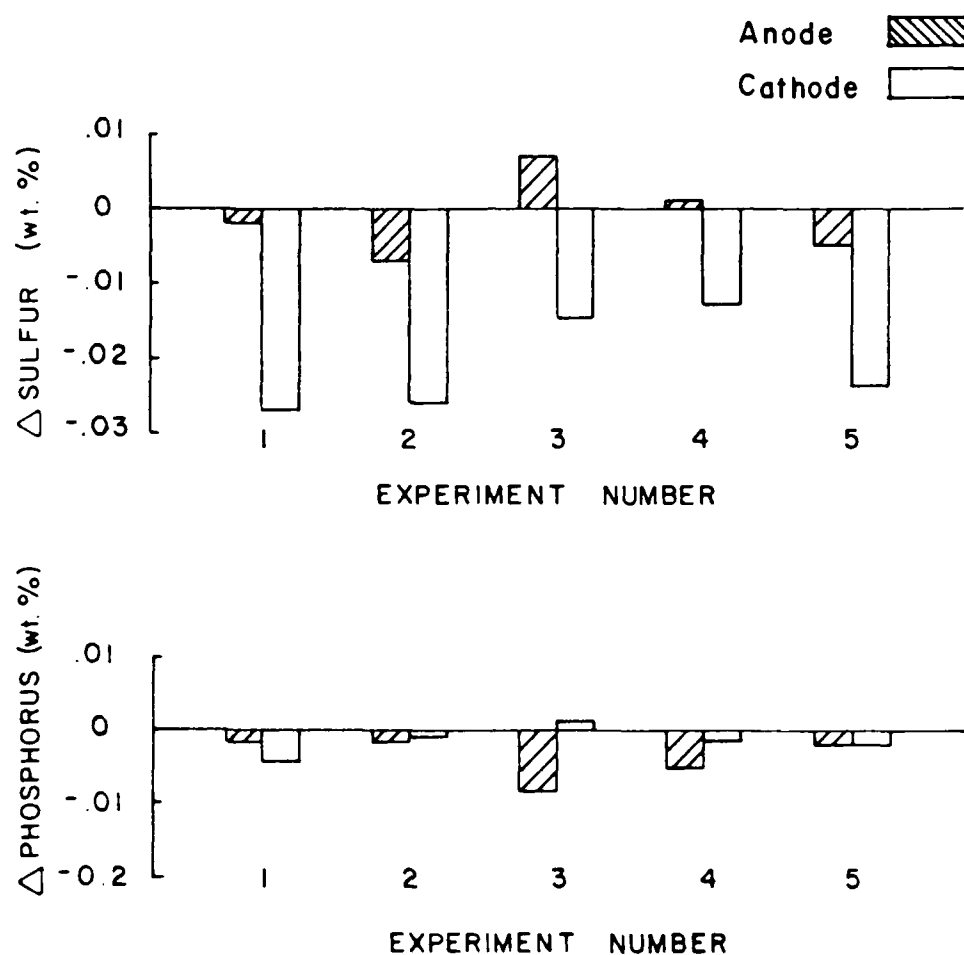


Figure 26 - Concentration changes for sulfur and phosphorus at the anode and cathode of the divided electrochemical cell.

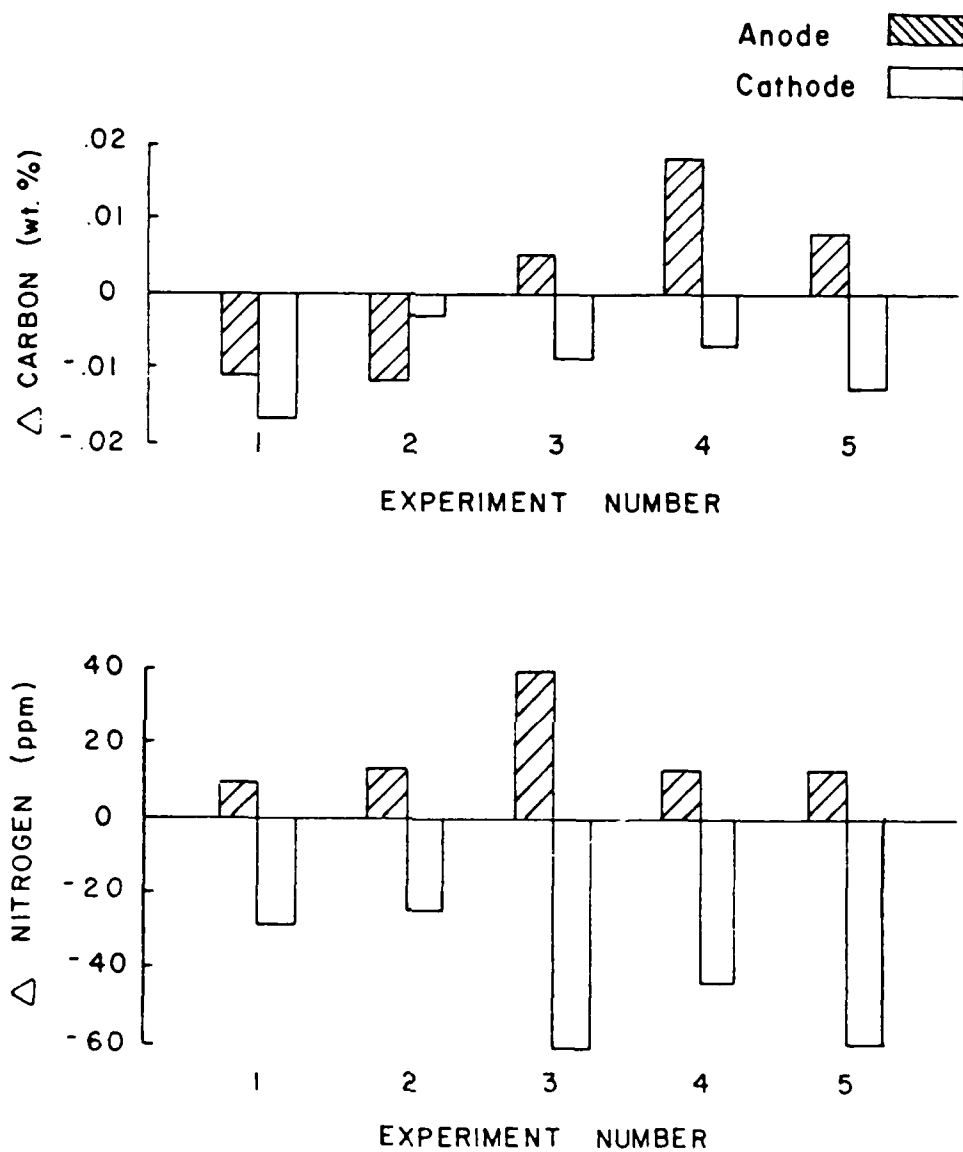


Figure 27 - Concentration changes for carbon and nitrogen at the anode and cathode of the divided electrochemical cell.

$$E \cong \frac{(\Delta C)WnF}{Q_t M} \quad (14)$$

Differentiating with respect to time the melting rate of the electrode can be substituted for the weight melted, and the welding current (rate of charge transfer) can be substituted for the total charge transferred:

$$E \cong \frac{(\Delta C)RnF}{IM} \quad (15)$$

where: R = melting rate of the electrode  
I = welding current

The product of the electrode surface area (A) and the current density (i) can be substituted for the welding current and Equation 15 solved to express the concentration change as a function of the current efficiency, the melting rate, and the current density:

$$\Delta C \cong \frac{EAiM}{RnF} \quad (16)$$

Equation 16 shows that the concentration change caused by an electrochemical reaction is directly proportional to the current efficiency and to the current density, and is inversely proportional to the melting rate of the electrode.

Figures 28 through 38 are plots of the current efficiency as a function of current density for electrochemical reactions involving iron, alloy elements, and tramp elements. Positive current efficiencies indicate an increase in the concentration of the element in the metal, and negative current efficiencies indicate a loss from the metal to the flux. Data for the reactions at the anode are indicated by round data points, and data for cathodic reactions are indicated by square data points. Figure 28 shows that anodic and cathodic iron reactions carry a large fraction of the current. The average current efficiency for iron oxidation at the anode is around 70%, and the average current efficiency for iron reduction at the cathode is around 50%. Figure 29 shows that the current efficiency for oxygen discharge and pickup at the anode is much larger than that for oxygen refining at the cathode, and Figure 30 shows that the current efficiency for aluminum reduction at the cathode is much greater than that for aluminum oxidation at the anode. These two sets of data account for the pickup of large amounts of oxygen and aluminum.

Figures 31, 32, and 33 for chromium, manganese, and silicon indicate large oxidation losses at the anode which increase with increasing current density, and smaller pickup at the cathode by reduction from the flux. The losses caused by oxidation are greater than the pickup by reduction from the flux; therefore, the net composition change for both anodic and cathodic reactions is an oxidation loss. Figure 34 shows that the current efficiencies for molybdenum reactions have the correct signs. That is, molybdenum is oxidized at the anode and reduced at the cathode.

The current efficiencies for electrochemical reactions involving sulfur, phosphorus, nitrogen and carbon are shown in Figures 35 through 38. Sulfur is refined at both electrodes, but the refining at the anode may be the result of thermochemical reactions. Phosphorus is refined at the anode and little change occurs at the cathode. This would be more typical of metallic behavior. Nitrogen shows typical nonmetallic behavior with a large amount of refining at the cathode which increases with increasing current density, and little or no concentration change at the anode. Carbon shows metallic behavior similar to that shown by phosphorus. An oxidation loss is observed at the anode with little or no change at the cathode.

Table III provides a summary of the current efficiency data for high and low current densities:



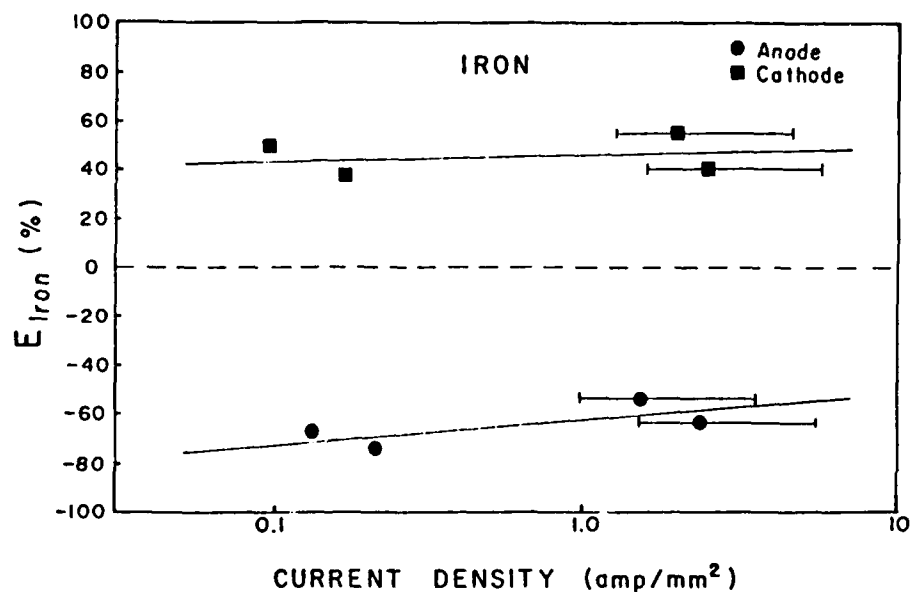


Figure 28 - Current efficiency for anodic and cathodic iron reactions as a function of current density. Positive and negative values indicate an increase or decrease in concentration.

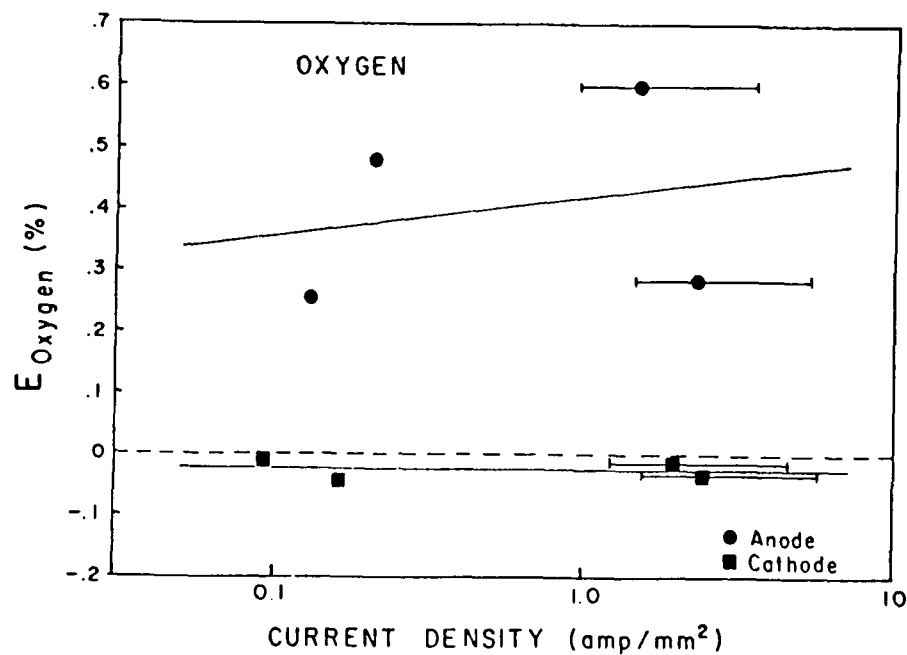


Figure 29 - Current efficiency for anodic and cathodic oxygen reactions as a function of current density. Positive and negative values indicate an increase or decrease in concentration.

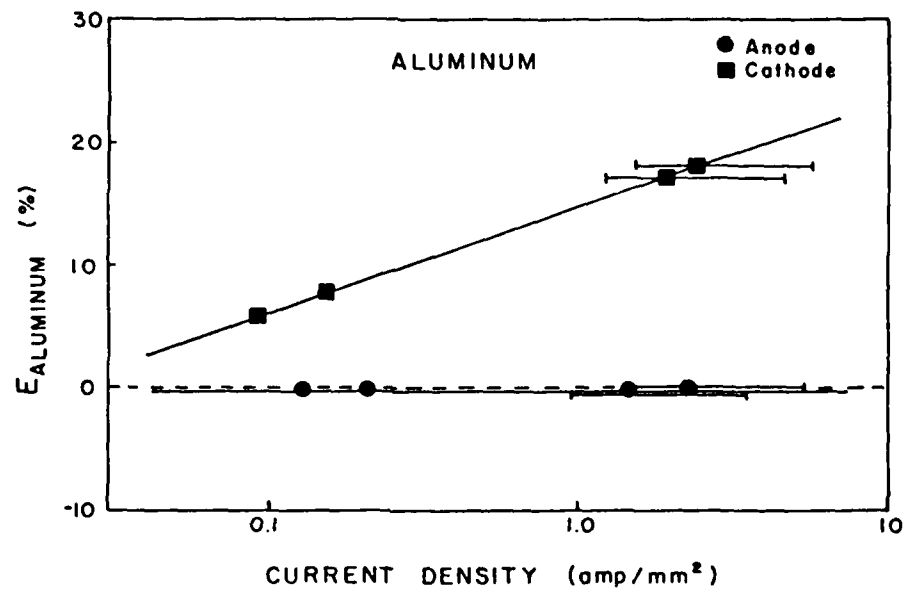


Figure 30 - Current efficiency for anodic and cathodic aluminum reactions as a function of current density. Positive and negative values indicate an increase or decrease in concentration.

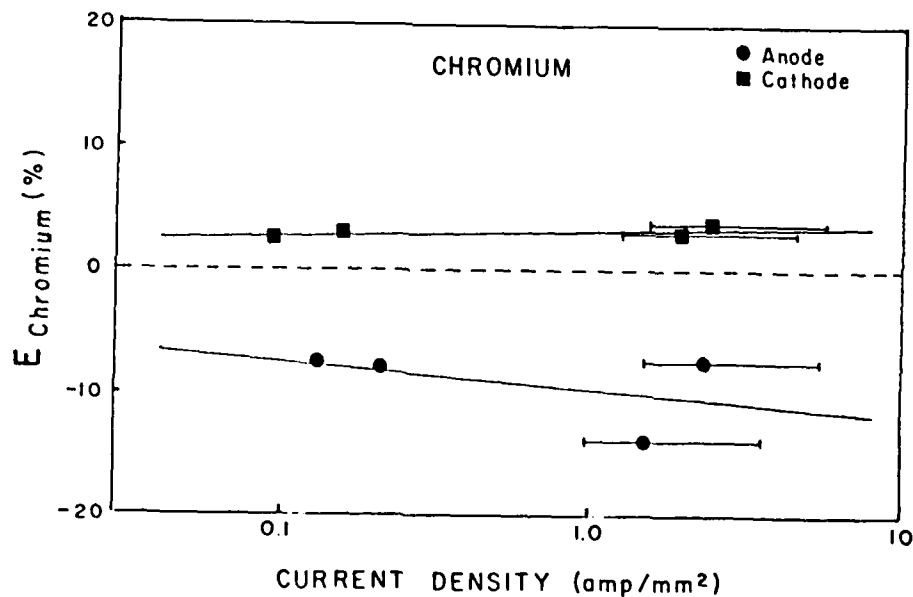


Figure 31 - Current efficiency for anodic and cathodic chromium reactions as a function of current density. Positive and negative values indicate an increase or decrease in concentration.

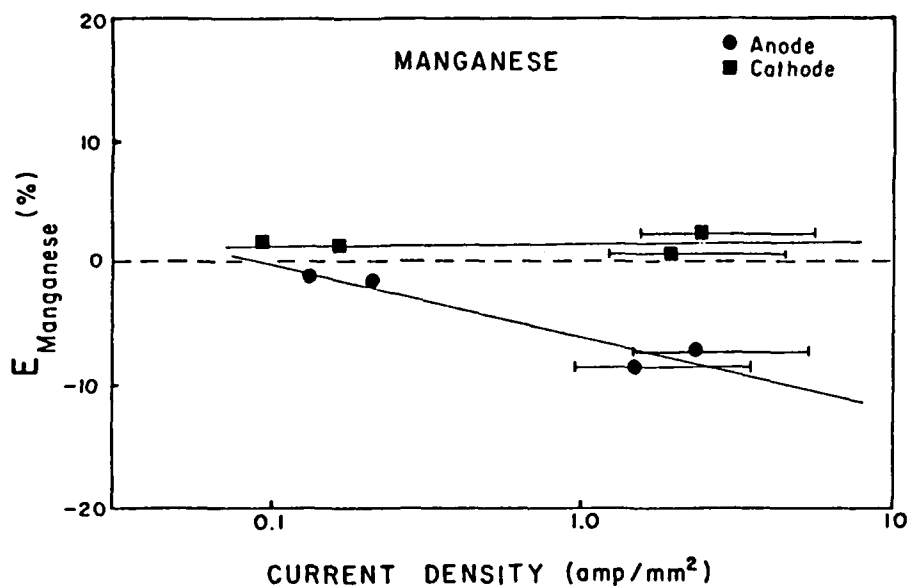


Figure 32 - Current efficiency for anodic and cathodic manganese reactions as a function of current density. Positive and negative values indicate an increase or decrease in concentration.

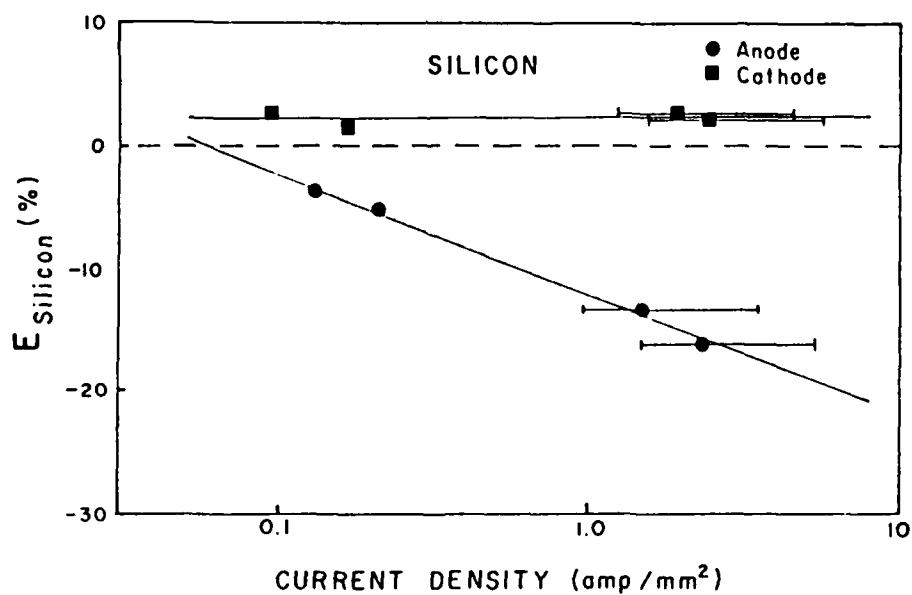


Figure 33 - Current efficiency for anodic and cathodic silicon reactions as a function of current density. Positive and negative values indicate an increase or decrease in concentration.

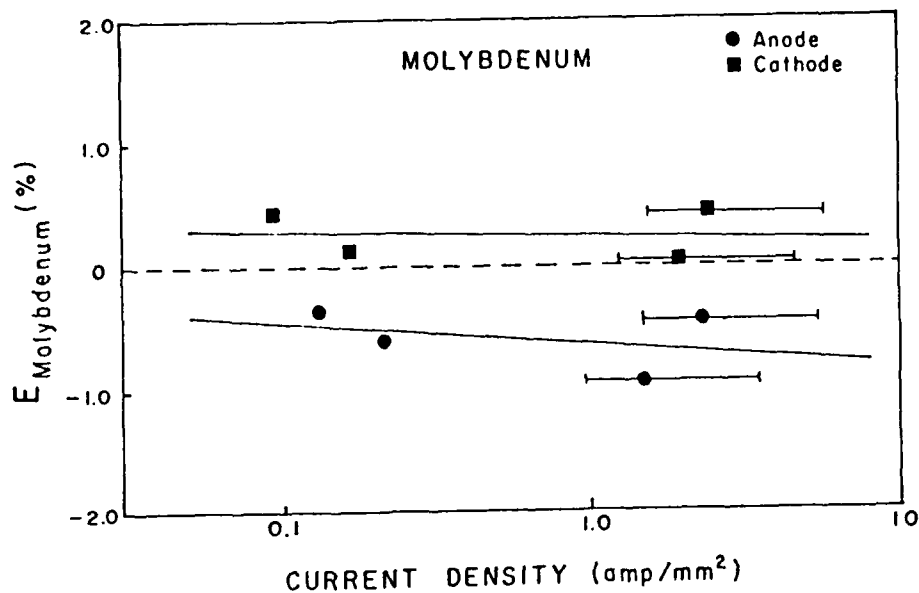


Figure 34 - Current efficiency for anodic and cathodic molybdenum reactions as a function of current density. Positive and negative values indicate an increase or decrease in concentration.

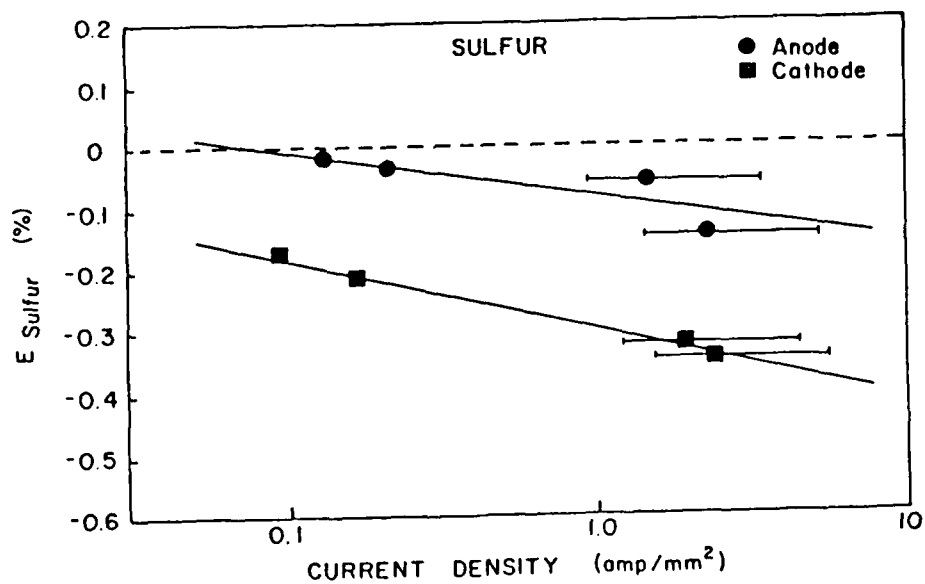


Figure 35 - Current efficiency for anodic and cathodic sulfur reactions as a function of current density. Positive or negative values indicate an increase or decrease in concentration.

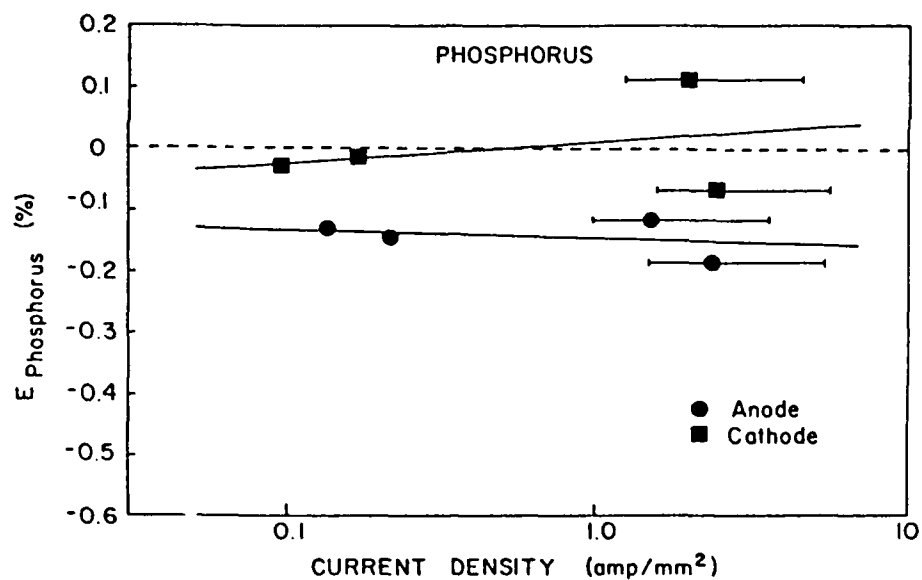


Figure 36 - Current efficiency for anodic and cathodic phosphorus reactions as a function of current density. Positive and negative values indicate an increase or decrease in concentration.

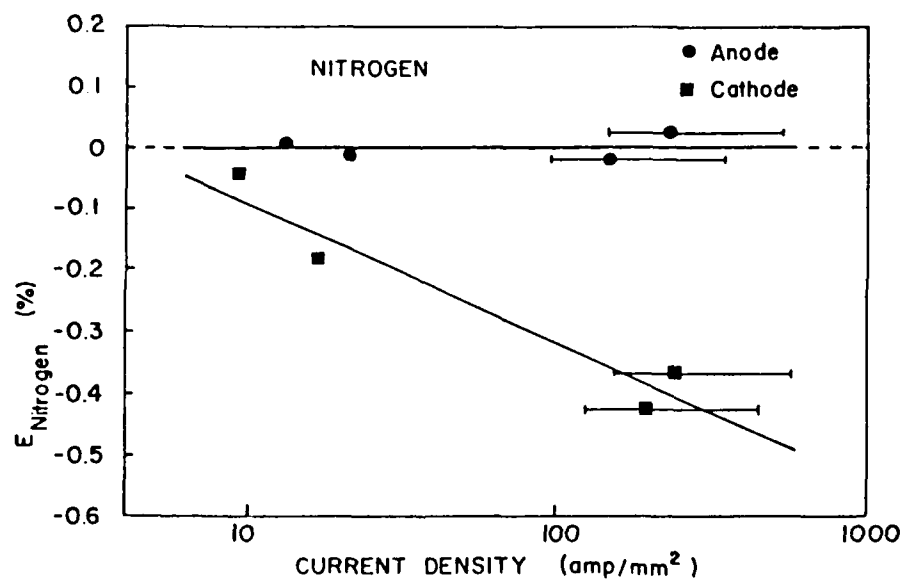


Figure 37 - Current efficiency for anodic and cathodic nitrogen reactions as a function of current density. Positive and negative values indicate an increase or decrease in concentration.

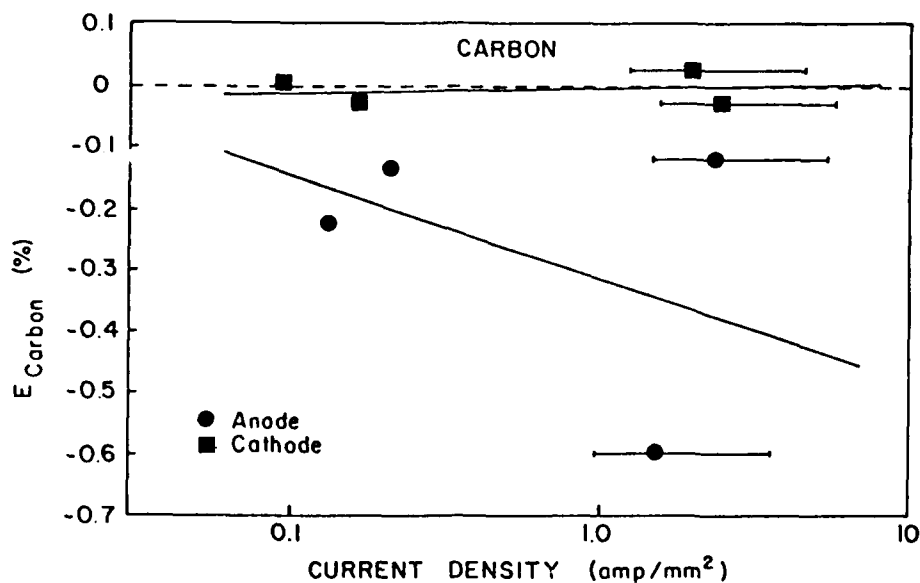


Figure 38 - Current efficiency for anodic and cathodic carbon reactions as a function of current density. Positive and negative values indicate an increase or decrease in concentration.

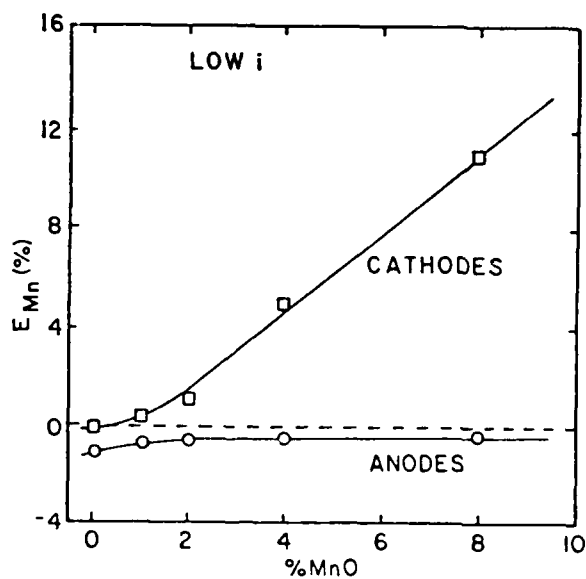


Figure 39 - Current efficiencies for anodic and cathodic manganese reactions as functions of the manganese oxide content in a  $\text{CaF}_2 - \text{MnO}$  flux.

TABLE III - AVERAGE CURRENT EFFICIENCY DATA

Element	Low Current Density		High Current Density	
	Anode	Cathode	Anode	Cathode
C	-0.18	-0.01	-0.36	0.0
Mn	-1.50	+1.33	-7.92	+1.54
Si	-4.34	+2.17	-14.61	+2.51
Cr	-7.66	+2.68	-10.61	+3.27
Mo	-0.48	+0.28	-0.69	+0.30
Al	-0.16	+6.78	-0.14	+17.61
P	-0.14	-0.02	-0.16	+0.02
S	-0.03	-0.20	-0.10	-0.33
O	+0.37	-0.03	+0.44	-0.02
N	-0.01	-0.12	0.0	-0.40
Fe	-70.94	+43.08	-58.25	+48.05
Total	85.81	56.70	93.28	74.05

The average current densities show that iron reactions carry the bulk of the current at both the anode and cathode. The oxidation of silicon and chromium carry a substantial fraction of the current at the anode, and the reduction of aluminum is important at the cathode at high current density. The totals show that from 86 to 93% of the current at the anode can be accounted for by the proposed reactions, while a smaller fraction of the current (57 to 74%) of the current is accounted for at the cathode. The lower total current efficiency at the cathode can be explained by the fact that calcium reduced at the cathode is not soluble in the steel, and can not be detected chemically. Overall, the current efficiency data shows that conduction is ionic rather than electronic.

A second set of electrochemical experiments utilized MnO additions to a CaF<sub>2</sub> flux to investigate the influence of activity in the flux on the electrochemical reactions. Experiments were performed with pure CaF<sub>2</sub> and with additions of 1, 2, 4, and 8% MnO, which covered MnO activities from zero to one. The experiment worked well at low current densities in the range of .10 to .20 amperes per mm<sup>2</sup>; but problems with arcing were encountered at the high current densities typical of the wire electrode.

Figures 39 through 42 show the anodic and cathodic current efficiencies as a function of the %MnO in the flux for reactions involving: manganese, chromium, silicon, and molybdenum. The data for manganese in Figure 39 shows that the current efficiency for cathodic manganese reduction from the flux increases linearly with increasing Mn activity in the flux. The current efficiency for anodic oxidation is small, and it decreases slightly with increasing flux MnO content.

Figure 40 shows the current efficiencies for anodic and cathodic chromium reactions increase slightly with increasing manganese oxide content in the flux. This influence may be caused by changes in Cr<sub>2</sub>O<sub>3</sub> activity with changes in MnO content. Figures 41 and 42 show that electrochemical reactions involving silicon and molybdenum are not influenced by the MnO content of the flux.

The prediction of composition changes caused by electrochemical reactions requires the establishment of a functional relation between the activity of a particular element in the flux and the current efficiencies for anodic and cathodic reactions. The influence of MnO additions to the flux on anodic and cathodic manganese reactions provides the necessary data to establish this model. Figure 43 is a plot of the current efficiencies for anodic and cathodic manganese reactions as a function of MnO activity in the flux. The manganese oxide activities are based on data from Mills and Keene (12). These data show that MnO saturation in calcium fluoride is reached at about 7 wt. %. Figure 43 shows that the current efficiency for cathodic manganese reduction increases parabolically with increasing MnO content in the flux, while the current efficiency for anodic manganese oxidation decreases parabolically. These data can be modeled to yield the current efficiency for manganese reactions as a power function of the manganese oxide activity in the flux:

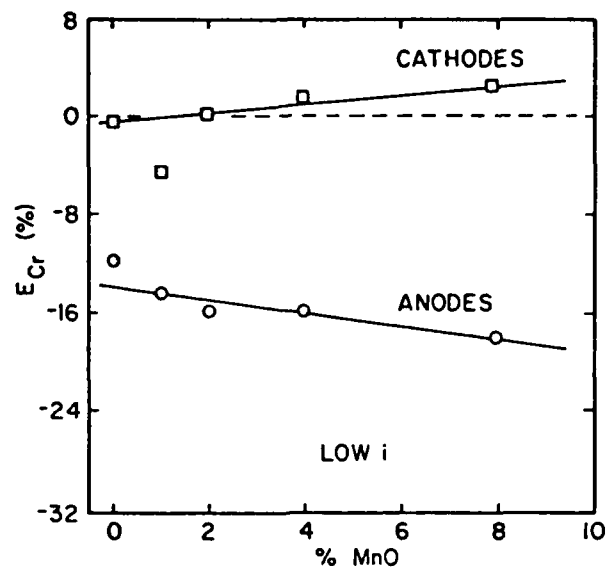


Figure 40 - Current efficiencies for anodic and cathodic chromium reactions as functions of the manganese oxide content in a  $\text{CaF}_2$  - MnO flux.

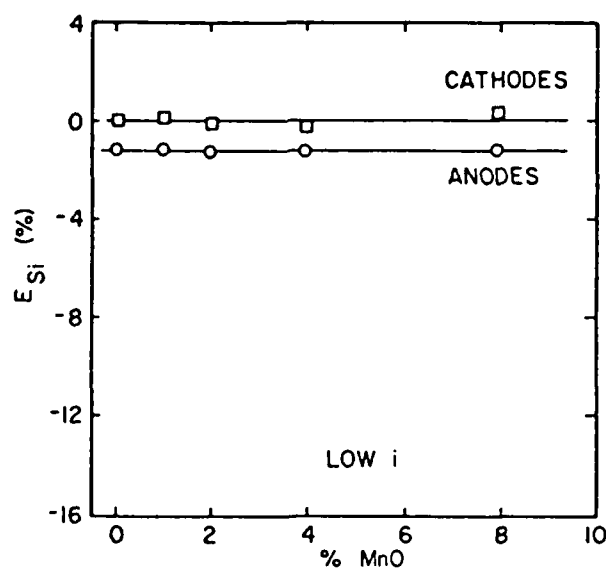


Figure 41 - Current efficiencies for anodic and cathodic silicon reactions as functions of the manganese oxide content in a  $\text{CaF}_2$  - MnO flux.



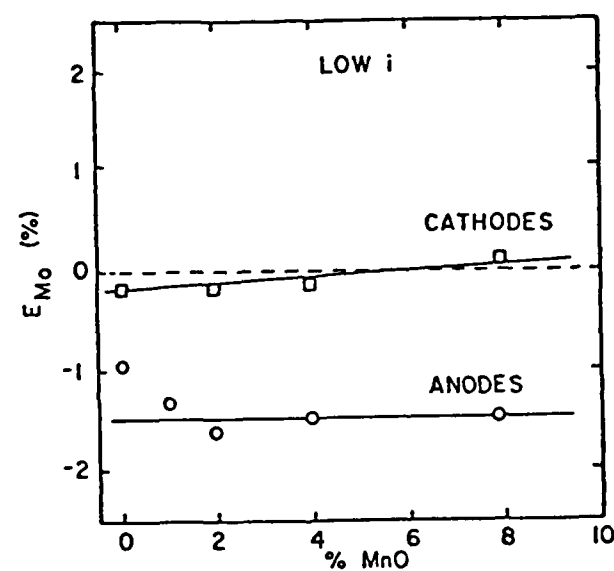


Figure 42 - Current efficiencies for anodic and cathodic molybdenum reactions as functions of the manganese oxide content in a  $CaF_2 - MnO$  flux.

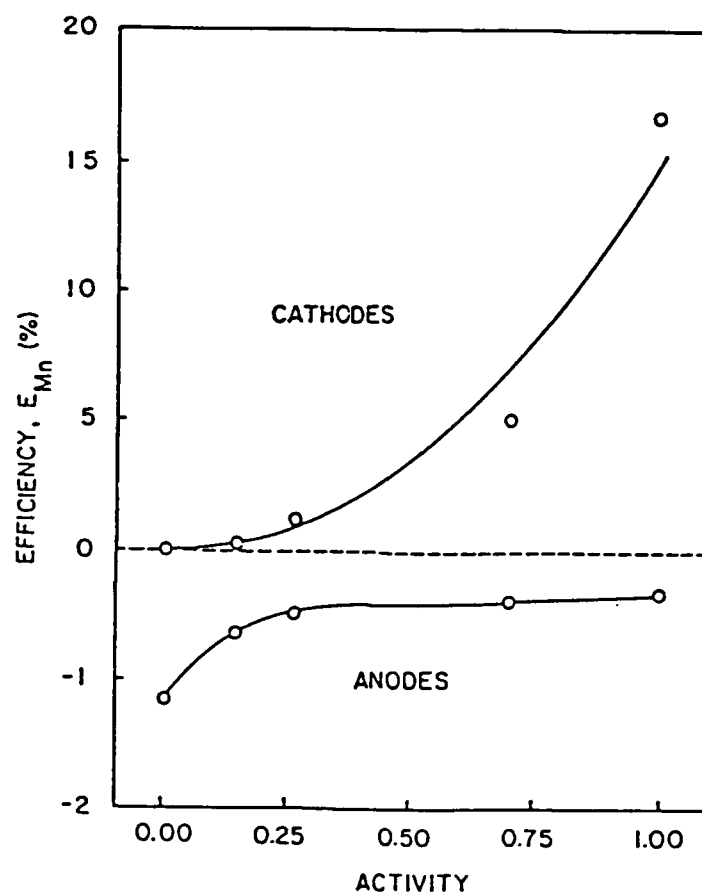


Figure 43 - Current efficiencies for anodic and cathodic manganese reactions as functions of MnO activity in a  $\text{CaF}_2$  - MnO flux.

$$\text{Cathodes: } E = 14.04(a_{\text{MnO}})^{2.03} \quad R^2 = 0.98 \quad (17)$$

$$\text{Anodes: } E = -0.35(a_{\text{MnO}})^{-0.27} \quad R^2 = 0.99 \quad (18)$$

The high correlation coefficients indicate an excellent fit, and the constants show the correct signs and magnitudes to fit the experimental observations. At the cathode the positive constants indicate that the current efficiency for manganese reduction increases with increasing manganese oxide activity in the flux. The negative constant and exponent for the anodic reaction indicates a decrease in current efficiency for manganese oxidation as the manganese oxide in the flux builds up. This correlates well with the time dependent composition changes observed for experiments conducted using the water cooled crucible.

The power function expression for the current efficiency as a function of flux activity allows for the modeling and prediction of chemical changes based on tabulated activity data. This applies to low current densities of 0.1 to 0.5 amperes per mm<sup>2</sup>. Arcing problems encountered at current densities of 1.0 to 10 amperes per mm<sup>2</sup> prevent revision the model for current efficiency as a function of the current density beyond that indicated by the experiments using the CaF<sub>2</sub> - 10% Al<sub>2</sub>O<sub>3</sub>. Figures 28 through 38 indicate a linear relation between the current efficiency and the logarithm of the current density.

The two sets of electrochemical experiments provide the basis for several conclusions:

1. The anodic electrochemical reactions in D.C. electroslag welding include the oxidation of iron and alloy elements and the discharge and pickup of oxygen anions from the flux.
2. The cathodic electrochemical reactions include: the reduction of iron and alloy elements. The reduction of metallic tramp elements, and the refining of nonmetallic tramp elements.
3. The concentration changes caused by electrochemical reactions are directly proportional to the current density and to the current efficiency, and are inversely proportional to the melting rate.
4. The current efficiency for an electrochemical reaction for any element may be expressed as a power function of the activity of that element in the flux.

#### ACKNOWLEDGEMENTS

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# EXPERIENCES OF ELECTROSLAG WELDING IN BRIDGE STRUCTURES

by

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## INTRODUCTION

After the introduction of electroslag welding as a new fabrication process in the early 1960's, it was not surprising that the economics of the process caused fabricators to consider it a potential one for large scale construction. The ability of the process to weld relatively heavy sections with a minimum of deposited weld metal and a relatively high deposition rate made its use feasible wherever heavy sections were to be welded. In bridge construction, the process proved itself to be economical for the welding of thick bridge girder joints such as flange butt splices, web butt splices, and transition joints. For members that were large and built up by welding, the splices in flanges and webs could be made prior to the welding of the web to the flange.

From the metallurgical standpoint, it was known that these welds had some significant differences from other welds made by conventional processes. For example, the entire weld joining two heavy plates is essentially one single pass. Moreover, the cooling conditions produced by the welding process are extremely slow and as a result grain sizes associated with the welds and their heat affected zones are much larger than found in conventional process welds. Some of the typical microstructures associated with these welds were described in the early literature by Paton.<sup>3</sup> Indeed the weld metals themselves have a pronounced grain orientation which could be varied as a result of the process. Thus the grain size and the grain orientation became a matter of control and in some cases, a matter of

concern.

Although the most prominent feature of the microstructure of these welds is the grain size, additional characteristics are also seen and may be important. The primary grain size seen appears to be solidification grain but, in fact, it is prior austenite grain size. The grains are seen because a boundary of ferrite outlines each prior austenite grain. This ferrite veining is a characteristic of most electroslag welds although it is not as prominent in the central fine grained region. Inside the prior austenite grains the weld microstructure is a fine mixture of ferrite and carbide in a Widmanstätten pattern. This is typical of most welds and thus is not unusual for electroslag weld grain interiors. As in other welds, there may or may not be a number of fine inclusions present.

#### REASONS FOR CONCERN

The size and shape of the crystals in the weld deposit and those in the heat affected zone were a matter of concern because of the general correlation between grain size and toughness. The American Welding Society adopted special requirements for electroslag welds in this regard (AWS D 1.1, Appendix C<sup>4</sup>), specifically that they meet a toughness requirement of 15 ft-lb Charpy impact energy at 0°F. There was also concern about cracking phenomenon in these steels. Because of the extremely high heat inputs during the process, it was assumed that hydrogen induced cold cracking or delayed cracking would probably not be a concern. Solidification cracking, especially in the case of welds where the elongated crystals were nearly perpendicular to the direction of welding had been shown to be a distinct possibility. Prevention of cracking was by control of the orientation of the weld crystals, called their form factor. Relatively early in the use of the process in the United States procedures were developed which allowed

control of the form factor such that highly orientated crystals producing a plane of weakness lying down the center line of the weld could be avoided. The microstructure of the heat affected zone was also a matter of some concern, although no testing was recommended in this zone in AWS D 1.1.

Because of the high heat associated with the weld, electroslag welding was never recommended for materials that were to be heat treated unless a full heat treatment would follow the welding process. It became a matter of course in many industries that electroslag welds in as-rolled or normalized material were given a renormalization or several renormalizations before they were put into service. In other cases, thermal stress relieving at or above 1150°C was applied in an effort to restore some of the toughness without going to a full renormalizing treatment. These procedures are expensive, and for bridge welding, renormalizing or stress relieving after welding was not practiced. And as a result, these welds were put into service in the as-welded condition.

As electroslag welding came into practice in the late 1960's and early 1970's, certain characteristic problems began to surface. While not appearing in the press, reports indicated that one of the recurring problems was solidification cracking in the center line of the weld, which has already been discussed. In general, the hot cracks that were produced were small, were statically loaded, and were not in a direction that would receive stress tending to open them. On this basis some welded structures containing these microcracks were put into service. It was also demonstrated that, on occasion, welds of low toughness could be produced, however, the requirement for Charpy impact toughness qualification tests on electroslag welds apparently provided assurance that inadequate toughness welds would be screened out.

By the mid-1970's, electroslag welding was well established as a fabrication procedure for heavy section splices in the bridge, building, shipbuilding, pressure vessel, and other industries. It appeared that the process was well understood and that adequate control had been exercised or could be exercised in production of welds. During this period of more extended application, it was found that nondestructive examination of these welds, particularly using ultrasonic techniques, was not easy. Because of the extremely coarse grain size, ultrasonic energy attenuation was fairly extensive in electroslag welds and the observation and recording of small defects proved to be difficult. Thus it was generally recognized that nondestructive inspection by ultrasonics was more difficult for these welds but it was believed that adequate procedures had been developed.

#### BRIDGE WELD STUDIES

The initiation of studies of electroslag welds from the standpoint of investigators at Lehigh University actually began in 1977 with the closing of a recently opened bridge on interstate route I79 near Pittsburgh, Pennsylvania. The fracture of one of two main girders in this structure, which contained electroslag welds, triggered an investigation of the welds both in the fractured girder and in the remaining parts of the structure. Investigation of the failure showed that the fracture path was completely through an electroslag weld and thus a detailed study of the nature of the crack initiation and propagation and of the properties of the weld in question was undertaken. Findings on this structure led to investigations of additional electroslag welded bridges both in that vicinity and throughout the state of Pennsylvania. This ultimately resulted in detailed examinations of material taken from seven bridges in the state of Pennsylvania and triggered similar investigations on electroslag welded



bridges in other states. One result of these investigations was the decision by the federal highway administration to forbid the continued use of electroslag welding in tension members on federally funded bridge projects until questions raised about the quality of the electroslag welds that had been studied thus far could be satisfactorily answered.

Since the examination of electroslag welds had its genesis in failure analysis rather than in a planned research program, the primary procedure used was to do an examination of welds that had already been produced. The approach was to study, identify, and catalog the characteristics of the welds rather than establishing a set of experiments which would deliberately manipulate certain variables to study their influence. In most cases, samples of production welds had to be removed from the existing structures in the field. As a result, it was not possible to remove large sections of these structures in order that extensive sampling could be accomplished.

By and large sampling was done by the removal of cylindrical core samples from one or more welds with an alloy steel core drill. The core samples were generally 75 to 100 mm (3 to 4 in.) in diameter and as a result the mechanical property specimens that could be obtained were nominal 6.5 mm ( $\frac{1}{4}$  in.) diameter tension test specimens and standard Charpy impact specimens. In a few instances samples of smaller size were removed, and in this case impact specimens were prepared by electron beam welding of ends on to the short length specimen blanks. In most cases, the only specimens that were obtained were those of the weld metal, although in a few instances some heat affected zone specimens were also removed. Since the cores were drilled transverse to the weld, specimens at various positions in the thickness of the weld could be sampled. Chemical analysis and metallography were also done on these specimens such that chemical

composition across the weld and a fairly extensive metallographic characterization was obtained in most instances. In other instances, only weldment metallography was available. For one or two welds, larger sections were available, and in these cases, compact tension specimens for fracture toughness evaluation were also fabricated. Electron beam welding was used to produce sufficient material for a standard compact tension specimen for some welds.

In addition to the weld sample cores that were removed from a number of structures, general examination of electroslog welds and other welds on these structures was often undertaken. This included not only nondestructive evaluation, but also the removal of paint and polishing and etching of the surface of the weld for macroscopic examination in the field. Thus a general survey of the visible appearance of electroslog welds in a number of structures was used to supplement the core samples.

The bridges examined were welded by a number of different fabricators, all of whom are experienced in bridge construction. In all cases, weld qualification plates submitted at the time of construction indicated that the welds produced by the proposed procedures should be satisfactory in soundness and have Charpy impact toughnesses meeting the specifications of AWS D 1.1 Appendix C. Moreover, each of the bridges in question was examined by X-ray analysis to a greater or lesser extent depending on the requirements of the state and were passed as being free of discontinuities which exceeded those permitted in the AWS Structural Code. Many were undoubtedly also examined by the fabricator during construction prior to final X-ray inspection. Final nondestructive examination was normally done by a contractor hired by the state rather than by the fabricator, usually in the fabricator's plant.

## RESULTS OF THE EXAMINATION

As a result of the inspection procedures a number of generic characteristics were found in the electroslog welds. In describing these characteristics, most of which are discontinuities or defects, it should be remembered that this does not imply that there were not large number of welds made by electroslog processes which were sound and apparently satisfactory for service. On the other hand, in some cases the defects observed were in high incidence. It would be unfair to condemn an entire structure because one or two defective welds are found. Some weld defects or discontinuities are a fact of life and most are repaired during fabrication. In this respect welding is no different from many other fabrication processes where quality control and proper procedure specifications are used to insure a minimum of defects. However, even if only a small number of uncorrected defects are found in a welded structure but these lie in critical members such that the whole structure is jeopardized by their presence, it must be considered serious whether they represent only a small portion of the welds or not.

The various characteristics observed in these welds, especially the characteristic discontinuities, will next be discussed without any particular significance to the order.

### Weld Repair

During the field examinations, one of the things that appeared to be most striking to the investigators was relatively high incidence of weld repair. As was described above, every welded structure will contain some weld repairs. However, in some of the structures that were examined weld repair appeared to be an almost continuous process with respect to the electroslog welds. In particular, weld repair of the fusion line in

several electroslog welded bridges was very common, so much so that field grinding and etching of weld surfaces showed repair at each fusion line on both sides of the plates was employed on virtually every single weld. In addition, there was a relatively high incidence, perhaps 20%, of welds in some of the structures that contained in-depth repair varying from one quarter of the thickness of the plate to those made through the plate thickness. It appeared that most repairs were made by the shielded metal arc process although in some cases where repair was extensive, submerged arc welding may have been used. Occasionally, multiple weld repairs were evident and numerous passes of weld metal were deposited to produce a sound joint. In other cases, weld repairs were on the surface only, and as a result underlying weld discontinuities were not removed.

In one bridge the weld repairs in at least one joint were very extensive, involving in depth multiple repairs at several orientations. These repairs occurred in a relatively heavy plate and the ultimate result was that defects of substantial size were left uncorrected in the repairs. This is illustrated in Figure 1. The weld defects were present in the bridge when it went into service and eventually led to brittle fracture of one girder of a two girder system. This required the bridge to be taken out of service for an extended period of time and extensive repair of not only the fractured area but also of other areas containing electroslog welds was required. The bridge had seen four months of service at the time of failure.

#### Fusion Line Cracking

One of the characteristic defects seen in electroslog welded structures was cracking along the fusion line on each side of the weld as seen in Figure 2. This type of cracking was found in at least three structures

and in one structure was found in more than 20 joints. The cracks ranged in depths from 2 mm ( $\frac{1}{16}$  in.) to as deep as 10 mm ( $\frac{3}{8}$  in.) and, being on the fusion line of butt splices in flanges, were transverse to the stress in the member. In several instances these cracks had been covered with a surface weld repair pass which did not penetrate to the root of the crack and thus left a substantial hidden weld defect. In one case, hydrogen induced cold cracking seemed to extend from the root of the repair weld on the electroslag weld fusion line.

As a part of the investigation of these members, cracks lying on the fusion line were broken open in the laboratory and their surfaces examined to determine their cause. Metallographic sample sections through these welds were also made as well as field examinations of cracked members. Both copper rich areas of the deposit and also particles or layers of metallic copper were found in the cracks. The presence of pure metallic copper suggests that the major cause for this type of cracking was the melting of the copper shoe which touches the surface of the plate at this location. This is seen in Figure 3.

Fusion line repair is sufficiently common that it is probable that fusion line "undercut" is a more frequent problem with these welds than has been reported. Because these regions have so frequently been weld repaired, it is not possible to identify copper from the mold shoe as being a primary cause of this phenomenon, indeed it may not. However, in those cases where deep cracking was observed and for which weld repair on the fusion line was not effective in eliminating the cracking, the crack surfaces were found uniformly to contain copper. Thus it is at least one of the potential causes for this type of cracking.

### Slag Pipes and Center Line Cracks

One of the bridge structures evidenced a series of "worm-hole" slag inclusions extending transverse to the axis of the weld and also to the plane of the plate. These slag pipes, seen in Figure 4, were fairly large in size and were, of course, an indication of some fabrication difficulty in this location. It appeared that the slag pipes were in association with either a very extensive change in welding perimeters, or were associated with a stop-start in the weld joint at this location. The slag pipes did not reach the surfaces of the plate as repair weld passes had been placed on the plate in order to cover the ends of the pipes. This discontinuity had passed through ultrasonic examination and was revealed by field radiography of the joint undertaken when grinding and etching of the weld surface indicated a substantial change in the weld width at this location.

The next of several center line cracks seen in Figure 5 was found to be associated with the slag pipes at this same location. The center line cracks lay transverse to the surface of the plate and parallel to the weld joint thus placing them in the most critical location as far as brittle fracture is concerned. Unfortunately these cracks were not identified either ultrasonically or radiographically but were actually discovered only after a cylindrical core containing the slag pipes was removed from the structure. From the appearance of the center line cracks, it is probable that they were produced by typical solidification phenomena. From their location, it also appears probable that they are associated with the premature freezing of the weld puddle related to difficulties with welding in that location. Correlation of this condition required complete removal of the areas containing cracking and cover plating of both this weld and a number of additional welds in the same structure for which radiography and

ultrasonic examination could not provide assurance that no additional undetected cracks of the same type existed.

#### Ferrite Vein Cracking

A defect also found in electroslog welded bridge structures was cracks lying in the ferrite regions surrounding the prior austenite grains. These have been called ferrite vein cracks. The cracks range in size from .05 mm (1/1000 in.) to as much as 18 mm (3/4 in.) commonly 5 mm (1/4 in.). The location of the cracks was found to be primarily on the coarse weld metal prior austenite grain boundaries extending from the fusion line towards the center of the weld. Some were also found in the fine grained region located toward the center of the weld. Typical ferrite vein cracks are seen in Figure 6. This type of cracking was found to be so extensive in one bridge structure that reinforcement of several hundred butt weld splices by use of cover plates was necessary. It was found that weld repairs had been undertaken on a few of these cracked joints. Unfortunately, the result of such repair was to produce larger cracks in the weld joints in the area adjacent to the repaired region, undoubtedly due to the shrinkage stresses produced by the weld repair. The ferrite vein cracking was not detected either ultrasonically or radiographically but was found only after core samples had been removed from the structure in question. Subsequent examination of a weld core containing defects and the radiographs taken from the same location revealed that the small cracks were faintly visible in the radiographs but extremely difficult to detect. Once the characteristics of the cracks were known, additional cracks could be identified from the radiographs of the structure.

The origin of these cracks has been positively identified by laboratory investigation to be hydrogen introduced into the welding process.<sup>6</sup>

After welding, as the temperature of the welded joint drops, cracking is apparently initiated at some temperature below 125°C (257°F). Subsequent cooling to room temperature produces the cracking. Hydrogen may be introduced into the weld joint in a number of ways. In laboratory studies it was found that humid air introduced above the slag puddle was sufficient to induce cracking and also cracking could be induced by the use of wet flux. Indeed, it was found that cracking could be induced by the surface condition of the wire used in the welding process. Baking of the wire prior to welding was sufficient to eliminate it. It is certain that some weld procedures that have been used in electroslog welding could introduce hydrogen, for example the use of wet asbestos to provide packing around the dams and the occasional use of oil to facilitate the motion of the core wire through the guide tube. Condensation of moisture on water cooled copper shoes on humid days could also be a source of hydrogen during welding. The number of cracks in this process can be very extensive; ten to twenty per inch of weld and, as described above, careless weld repair can be ineffective.

#### Mechanical Properties

Removal of samples from a number of welded bridge structures made possible some mechanical property characterizations. As indicated above, property investigations were limited to those specimens which could be readily prepared from the samples removed from the existing bridges, that is, those which could be prepared from a 67 to 100 mm (2½ to 4 in.) diameter core sample. Strength properties as determined from material removed from these welds appeared to be satisfactory and to meet those specified for the weld joints. On the other hand, Charpy impact tests on these electroslog welded joints uniformly failed to meet the toughness require-



them in the AWS Structural Welding Code D 1.1, Appendix C, and which were met by the weld qualification plates. These results are in keeping with other published reports.<sup>7</sup> The spectrum of toughnesses observed in the welds are seen in Figure 7. Although the toughness specification is complex,<sup>8</sup> it should be noted that, in general, weld toughnesses less than 13.5 J (10 ft-lb) are not permitted and the average toughness at 0°F in the welded joint is to be 20 J (15 ft-lb) at the specified test position in the weld. As can be seen, the most frequent impact energy is on the order of 8 J (6 ft-lb), and the average toughness, while equaling 20 J (15 ft-lb) included a large number of specimens with toughnesses of less than 13.5 J (10 ft-lb). Most of these welds would have been disqualified according to the AWS specification. The specimens shown in Figure 7 are from the AWS specified test position. Tests from other positions, such as the weld center, gave lower values. This has also been reported by others.<sup>7</sup>

It is only fair to note, however, that the toughness specification for the weld metal is not the same as that for the plate. For bridges built in the United States prior to 1974, there was no uniform toughness specification for the plate materials. Thus it was possible in electroslog welded bridges to have plate material that would have had toughnesses as low or lower than those found in the welds. Current bridge specifications require plate toughnesses that vary with locality but for most of the continental United States they would be in the range of 20 to 34 J (15 to 25 ft-lb) at 40°F. Weld metal toughness requirements are generally higher than that required of plates because of high levels of residual stresses and the potential incidence of defects. For fracture critical bridge members, it could be as high as 25 ft-lb at -20°F.

The point at issue here is not whether the specification was correctly

established either for the electroslog welds or for the bridge structures themselves, but rather that the welds uniformly failed to meet the toughness requirements which were placed upon and were agreed to by the bridge fabricators. The toughness of the welds was contributory to the difficulties in retrofitting the structure. For example, when it was established that center line cracking was present in a thick flange of a two girder bridge and the toughness was 8 J (6 ft-lb) at 0°F, the available options in terms of preserving the integrity of the structure were substantially reduced. In that particular case cover plating of all the remaining electroslog welds of the structure was undertaken as a safety measure.

#### SUMMARY OF THE INVESTIGATION

As the field observations on the electroslog welded bridge structures progressed, it soon became evident that a fairly large number of structures had passed into service containing measurable defects which had not been detected by nondestructive inspection. In all fairness, it must be said that this problem does not exist only with electroslog welds. A number of other welded bridge structures given the same inspection have been found to have defects of significant size after entering bridge service.

From the examination of the extensive repair on these welds, however, it would be unfair to imply that the quality control problems should be laid primarily on weld inspection, for it is apparent that a number of weld defects were detected during fabrication and that some repairs were attempted. The extensive nature of these repairs indicates that the welding process could not have been in good control. Since it is generally uneconomical to do extensive weld repair, better control of the welding process would not only result in superior quality welds but ones that are also more cost effective as well. In a number of cases, weld defect repair was

attempted unsuccessfully. Moreover, the properties of the weld metal deposited in some of these repairs was inferior to the electrosag weld which it replaced. In one notable instance the repair weld metal had lower toughness and larger cracks than the electrosag weld in which the repairs were found.

As was described in the introduction to this paper the use of electrosag welding in bridge tension members is presently forbidden under FHWA rules for projects which are built with federal funds. Most state highway department have followed this lead and forbidden its use in their respective states. On the basis of these findings, it is possible to understand why this move was taken. The steps that will be required to permit restoration of the process as an acceptable one in highway bridge construction are also clear. As a minimum, it will be necessary to establish that the factors in the electrosag welding process which have led to the cracking phenomenon found in bridges are understood and may be controlled. Secondly, it will be necessary to demonstrate that weld repair of these joints can be undertaken effectively, and that the repairs will produce sound, reliable joints. Third, it will be necessary to demonstrate that weld metal of acceptable toughness can be deposited by this process. That may require re-examination of the toughness specifications for electrosag welds, but in any case, whatever that specification may be, it will be necessary to demonstrate that electrosag welds can reproducibly meet the specification, not only in the qualification welds but in the production welds as well. And finally it will be necessary to demonstrate that nondestructive examination techniques for electrosag welds can reliably detect defects of sufficiently small size to insure the integrity of structures made by this process. When these steps are taken, the use of

the electroslog welding in bridge structures can again be undertaken with confidence.

## REFERENCES

1. American Welding Society, Electroslog and Electrogas Welding, Chapter 7, Welding Handbook 7th edition, Volume 2, pp. 225-247.
2. Benter, W. P., Jr., "Electroslog Weldments in Bridges," NCHRP Project 10-10, Research Results Digest 74, June 1975 and "Acceptance Criteria for Electroslog Weldments in Bridges," NCHRP Project 10-10, Phase 1 Report.
3. Paton, B. E. ed. Electroslog Welding 2nd Edition, American Welding Society, Miami, Florida, 1962.
4. American Welding Society, AWS Structural Welding Code, ASW D 1.1-72, American Welding Society, Miami, Florida, 1972.
5. Ramos, J. B. de S., Pense, A. W. and Stout, R. D., "Fracture Toughness of Electroslog Welded A537 G Steel," Welding Journal, Volume 55, No. 12, December 1976, pp. 389s-399s.
6. Stout, R. D., Davenport, S. A., Qian, B. N. and Pense, A. W., "Ferrite Vein Cracking in Electroslog Welds," The Welding Journal, Volume 60, 1981.
7. Culp, J. D., "Electroslog Weldments Performance and Needed Research," The Welding Journal, Volume 58, No. 7, (July 1979), pp. 27-41.
8. The requirement is that five specimens are tested, the highest and lowest to be discarded. The remaining three are evaluated as follows:  
  
"If the value for more than one of the three specimens is below the minimum average requirement, or if the value for one of the three specimens is below the minimum value permitted on one specimen, a retest shall be made, and the value of all the three specimens must equal or exceed the specified minimum average value. Such a retest shall be permitted only when the average value of the three specimens equals or exceeds the minimum value permitted on the specimen."

AWS Structural Welding Code D 1.1, Appendix C.

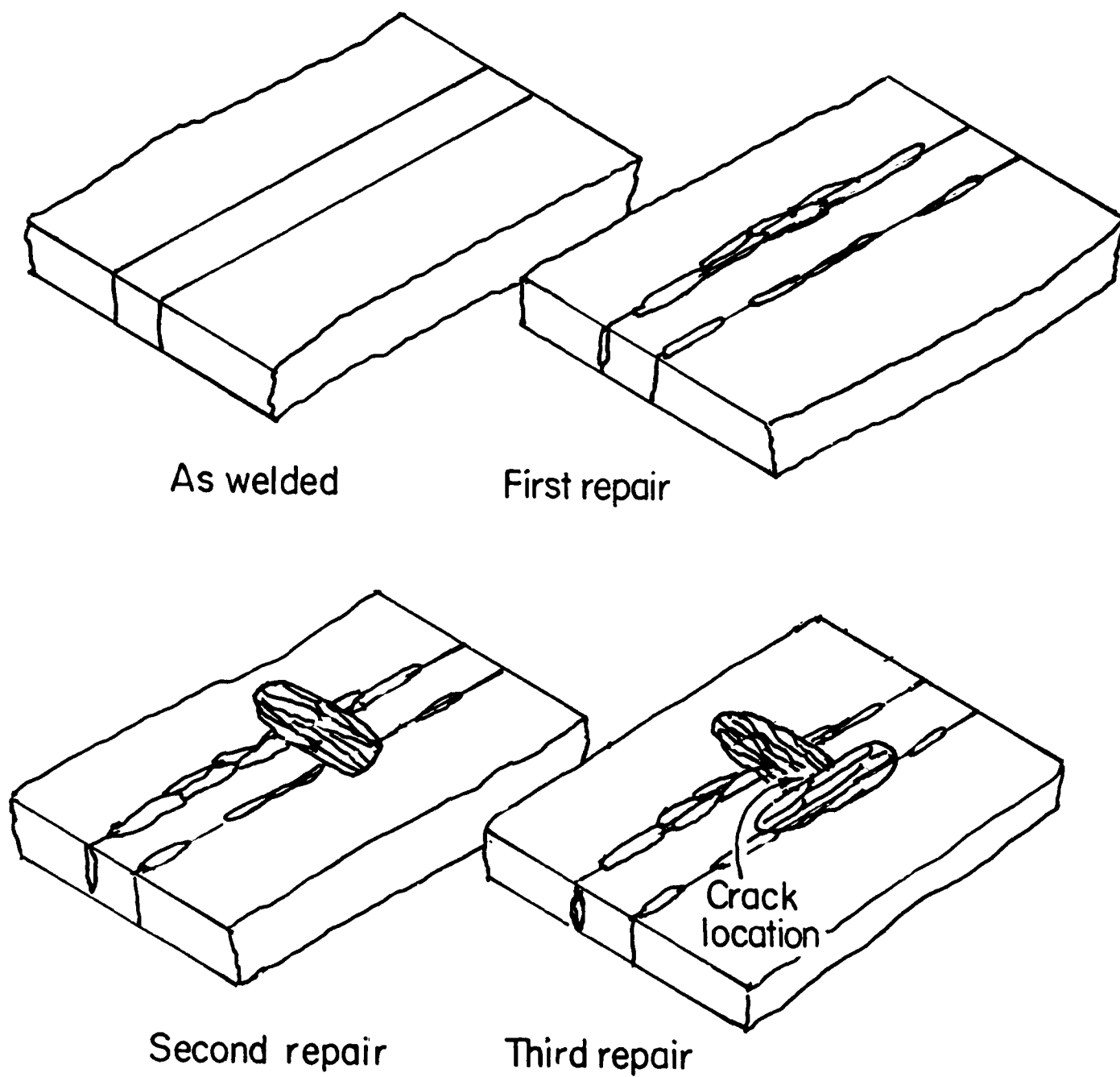


Figure 1 - Weld repair in an electroslog weld.

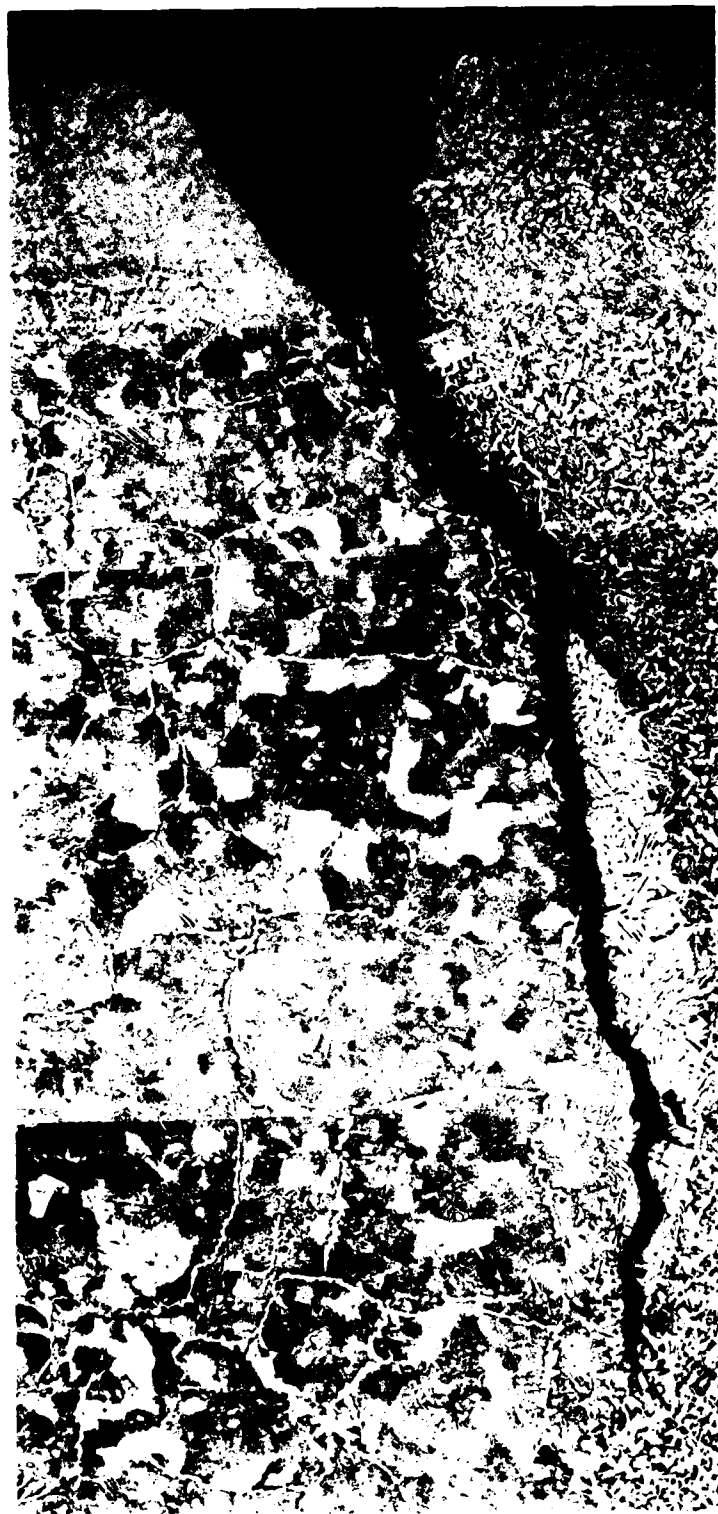


Figure 2 - Fusion line crack in electroslag weld. Nital etch, 40X.

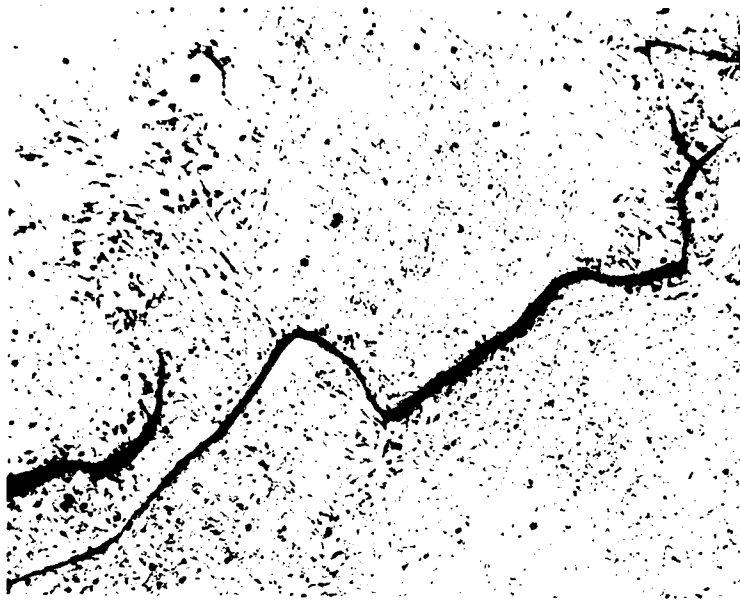


Figure 3 - Metallic copper seen in fusion line crack area. Note cracks are intergranular. Nital etch, 50X.



Figure 4 -- Transverse slag pipes in electrosag weld. Nital etch, ~ 1X.



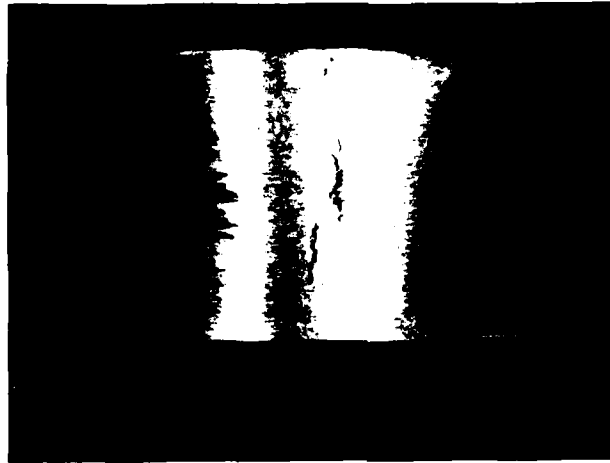


Figure 5 - Longitudinal crack in same electroslag weld as in Fig. 4.  
Nital etch, ~ 1X.

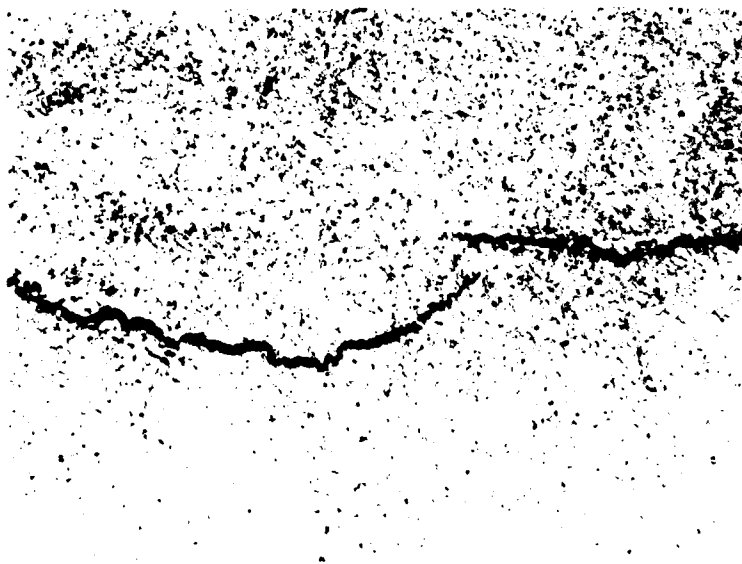


Figure 6 - Ferrite vein cracking in electroslag weld. Nital etch, 50X.

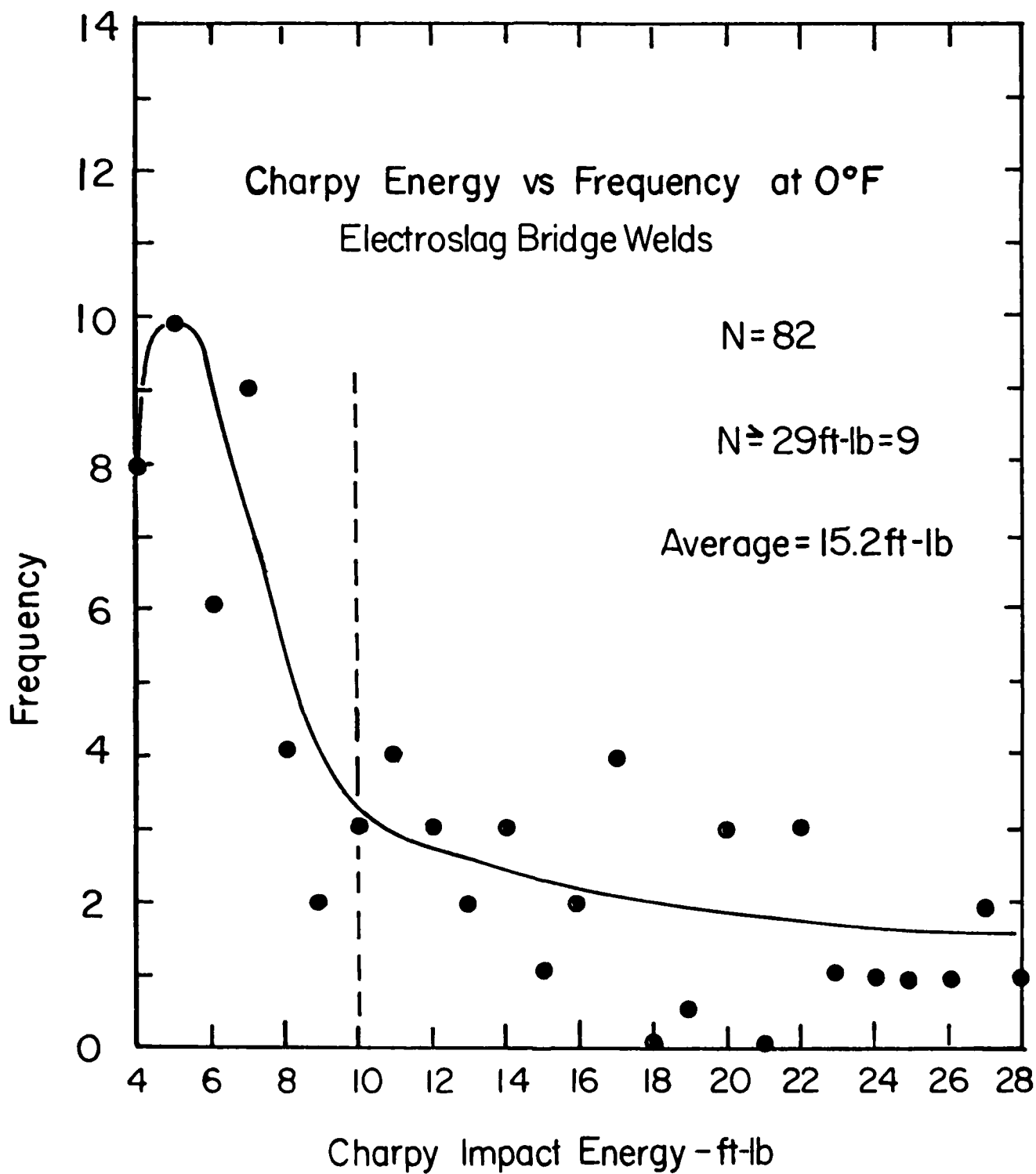


Figure 7 - Charpy toughness of electroslag bridge welds.

**ELECTROSLAG WELDING OF CYLINDER HEAD**

**BY**

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**PRESENTED TO**

**WORKSHOP ON "ELECTROSLAG PROCESSING FOR MARINE APPLICATIONS"  
U.S. NAVAL ACADEMY  
ANNAPOLIS, MARYLAND  
MARCH 5 AND 6, 1985**

**ABSTRACT: ELECTROSLAG WELDING HAS BEEN IN USE FOR APPROXIMATELY EIGHT YEARS AT THIS LOCATION. COST REDUCTION AND QUALITY IMPROVEMENTS HAVE BEEN SIZEABLE. FURTHER IMPROVEMENTS MAY BE FEASIBLE BY USING DIFFERENT PWHT PROCEDURES.**



## ELECTROSLAG WELDING AT BETHLEHEM-BEAUMONT

### BACKGROUND AND END USE OF PRODUCT

Our site-designed offshore drilling rigs for 100-foot, 200-foot, and 250-foot water depths are built with three tubular columns as shown in the attached brochure. The columns are pierced for entry of the AISI 4140 jacking pins which are used to lower the mat to the ocean floor and raise the platform to proper operating position. The platform area adjacent to the three columns is known as the jack house.

In each jack house there are, depending on water depth, four or six cylinders whose cutaway view appears in the attached Figure 1. In the cutaway view, the AISI 4142 piston rod, AISI 4340 cylinder, AISI 1040 blind end head, ASTM A572 Grade 42 clevis lug, AISI 4140 pin, and ASTM A131 Grade EH36 cylinder foundation and boss plate can be seen. The blind end head and clevis lug are electroslog welded as shown on Figure 2. The spacing for the weld nugget is shaded in. Its size is the product of "B" x "C" x weld gap for various models. A sump holding steel wool, to provide ignition, and an upper runoff tab, omitted for clarity of Figure 2, are provided in order to make a satisfactory weld.

### PRODUCING THE WELD

The weld is made using the site-built device shown in Figure 3. Linde 1/8-inch Number 36 wire is fed from the coils through two rebuilt heads from old submerged arc equipment to which two Linde 4-foot long Number 896 F21 Type S consumable tubes have been attached. A small motor with a cam linkage to provide oscillation and dwell has been added.

Initially 250-degree preheat fed through the AISI 1040 blind end is applied. Ignition against the steel wool is obtained; and when melt puddle clears the sump, the preheat torch is cut off. Linde 124 flux is added as needed to maintain flux cover puddle. When upper runoff tab is reached, the arc is broken, completing the weld. The machine (Figure 3) is shifted to right or left and prepared to weld the next head. Welded head is removed from jig, sump and runoff tab are removed, the assembly is wrapped in insulation material to cool. After cooling, the head is ultrasonically inspected and normalized at 1625 degrees Fahrenheit to 1650 degrees Fahrenheit.

#### WELD CERTIFICATION

ABS approved Welding Procedure 333 is attached. On pages 2, 3, and 4 are sketches and details of what took place in 1981. At that time we altered our previous procedure (Number 245) from 10 strokes per minute with a 2-second dwell at end of stroke to 48 strokes per minute without dwell. This improvement reduced the excessive re-machining of the copper shoes due to warpage. It also eliminated having to occasionally use air-arc and SMAW to "dress up" the distorted vertical face of the electroslog weld. On pages 5, 6, 7, and 8 of Welding Procedure 333, the mechanical testing results in the normalized condition are presented. A key point in this data is the marco-etch specimens of before and after normalization. These prove the need for PWHT. They also indicate material selection may be improved upon.

## QUALITY AND COSTS

Over 800 heads of the three different sizes shown on Figure 2 have been welded by this process over an eight-year period. Only ten heads have needed weld repairs and two had to be scrapped, which is a 1.5 percent reject rate. Formerly, approximately 300 of the two smaller heads were manually welded by using a 45 percent double bevel joint. Minimum time to complete a head was 56 man-hours. Reject rate was about 35 percent; thus the average welding time per head was about 70 man-hours.

With the electroslog process, welding time per head is 4 man-hours. This includes adding sump and upper runoff, and removing same. Thus a 66 man-hour saving per head was obtained by this change.

## PROCESS ANALYSIS AND EVALUATION

At the lower left corner of page 4, the operational data used in the procedure is shown thusly:

Amperes	700	Horizontal Traverse	4 in.
Volts	45	Horizontal Speed	3.2 IPS
Vertical Speed	.29 IPM	Oscillation (page 2)	48 strokes/minute

From the above, these results are gleaned:

Horizontal travel in 1 minute is

$$3.2 \text{ IPS} \times 60 = 192 \text{ in.}$$

Depth of one horizontal traverse is

$$.29 \text{ IPM} \div 48 \text{ strokes} = .006042 \text{ in.}$$

Heat input per inch of vertical rise is

$$(700 \times 45 \times 60) \div .29 = 6,517,241 \text{ j}$$

Heat input per inch of horizontal run is

$$(700 \times 45 \times 60) \div .00604 = 6,517,241 \text{ j}$$

Theoretical deposit in 1 minute is

$$.29 \text{ IPM} \times 1.25 \text{ in.} \times 4 \text{ in.} = 1.45 \text{ cu.in.}$$

Theoretical weight in 1 minute is

$$1.45 \text{ cu.in.} \times .284 = .4118 \text{ lb.}$$

Theoretical deposit of horizontal stroke is

$$.030209 \times .284 = .00858 \text{ lb.}$$

Time to produce 17-inch vertical weld is

$$19 \text{ in.} \div .29 = 65.5 \text{ minutes}$$

Total weight of 17-inch vertical weld per lug is

$$85 \text{ cu.in.} \times .284 = 24.15 \text{ lb.}$$

Weld deposit per man-hour per lug is

$$24.15 \div 65.5/60 = 22.12 \text{ lb./hr.}$$

The theoretical amount of heat required to melt 1 pound of steel is approximately 676,500 joules, and the heat required to melt the .4118-pound deposit is 278,582 joules. Two etch coupons, sketches of which appear on pages 9 and 10 of Welding Procedure 333, show the shape of the as-welded and normalized completed welds. These are 100 percent greater than the original spacing (1½ in. x 4 in.). There is at least .8236 pound of metal in the molten state in 1 minute. Thus there is a dilution rate of 50 percent of base metal in the final product, and 557,164 joules are required to attain the same. The approximate total heat to form the finished nugget is (557,164 x 655) 36,494,242 joules. The completed 750-pound subassembly, which has been a small steel furnace and radiator



during welding, has average overall surface temperature of 400 degrees Fahrenheit. This would equate to heat retention of over 37,000,000 joules.

The total heat input is  $6.517 \times 10^6 \times 19 = 12,383 \times 10^8$ . Subtracting the heat required and the heat retained leaves 50,333,337 joules that may have been partially wasted.

#### FUTURE

Some things that need consideration:

1. Is the use of the heat input formula adequate for this type of operation? Or, would the melt off approach as illustrated above be better?
2. Consideration of limits on heat zone hardness could be lead to reducing or eliminating PWHT.
3. Examine the HSLA and precipitation hardening steels more closely than in the past. Secondary operations such as PWHT add costs to the end product that may overcome savings obtained by the electroslog process.

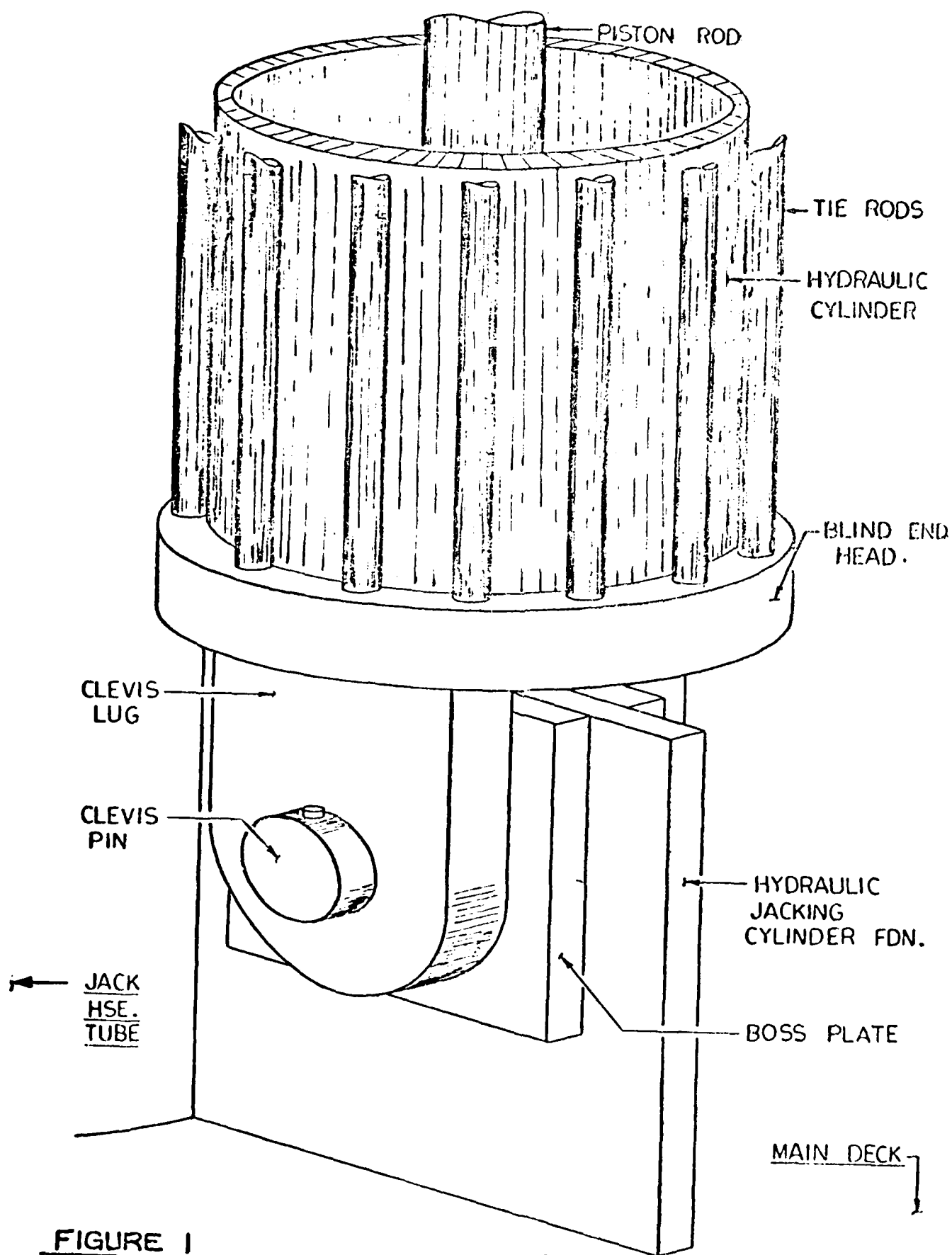
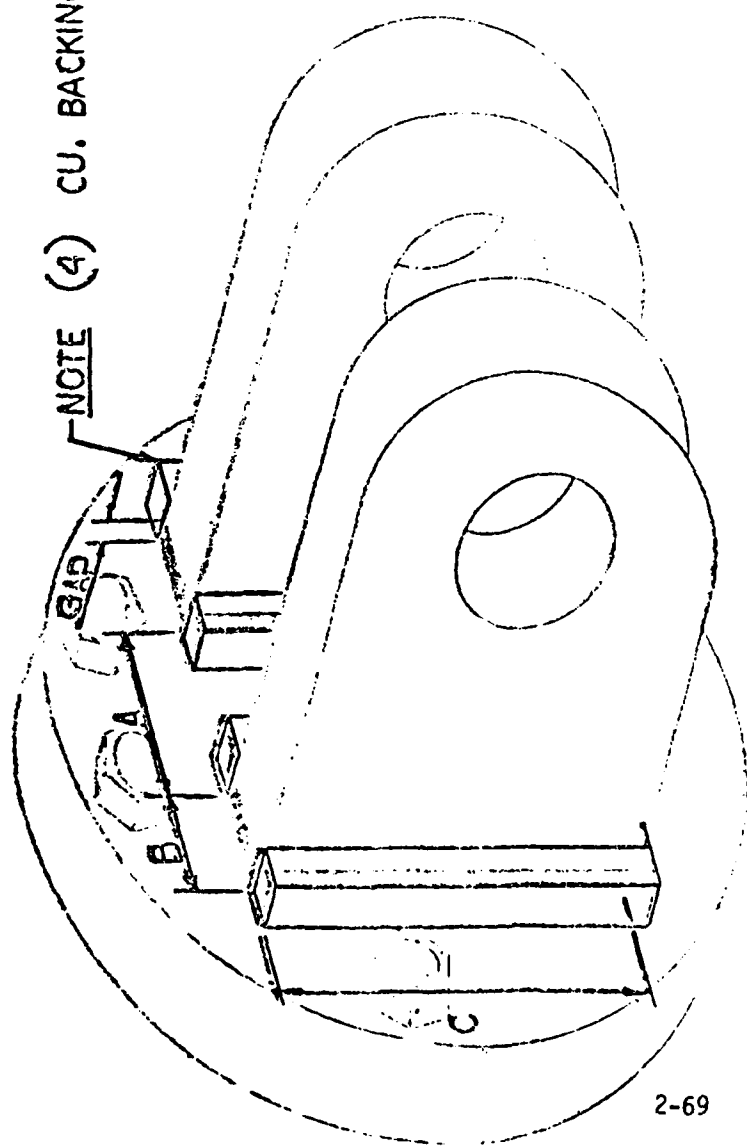


FIGURE 1



2-69

DESCRIPTION

<u>MODEL NO.</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>WELD GAP</u>	<u>WRENCH CLEAR</u>	<u>LUG SIZE</u>
4936	4 1/2"	2 1/4"	17 1/2"	1 1/4"	3 3/4"	11 1/2" X 2 1/4" X 0' - 10 1/2"
4938	9 1/8"	5 1/2"	20"	1 1/8"	7 3/4"	20" X 5 1/2" X 2' - 0 7/8"
4943	7 5/8"	4 1/2"	17"	1 1/8"	10 15/16"	17" X 4 1/2" X 1' - 11 3/8"

FIGURE 2

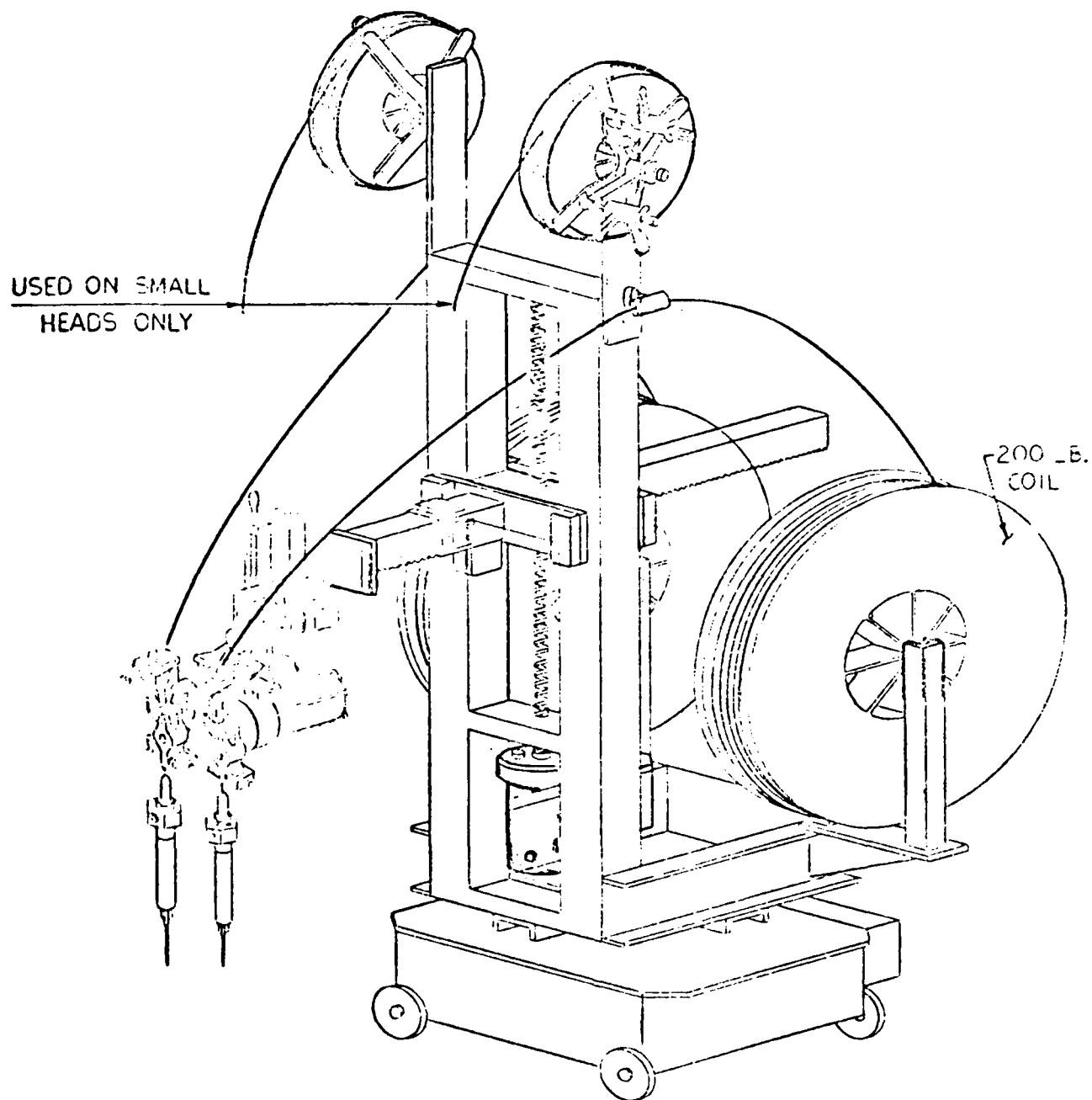


FIGURE 3

# American Bureau of Shipping

*Sixty-five Broadway*

*New York, N. Y. 10006*

12 November 1981

*Report* DR/gm  
*File Ref* ML 4-7

Bethlehem Steel Corporation  
Engineering Department  
Box 3031  
Beaumont, TX 77704

Subject: W.P. 333 Electro-Slag Welding of A572 Gr.  
42 to AISI 1040

Attention: Mr. L. A. Barrow,  
Chief Engineer-Production.

Gentlemen:

We have received your letter of 21 October 1981 together with enclosures relative to the subject and in regard thereto we would advise as follows:

The subject weld procedure is considered satisfactory and therefore may be used for Bureau classed vessels provided the Rules are adhered to in all respects and production welding and nondestructive testing of the completed welds are to the local Surveyor's satisfaction.

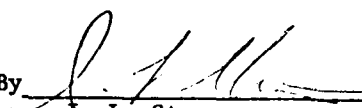
We are returning one (1) copy of the subject procedure stamped with the "Eagle" to indicate our review.

Very truly yours,

AMERICAN BUREAU OF SHIPPING

W. M. Hannan  
Vice President

By

  
L. L. Stern  
Asst. Chief Surveyor  
Materials Engineering Section

RECEIVED

16 NOV 1981

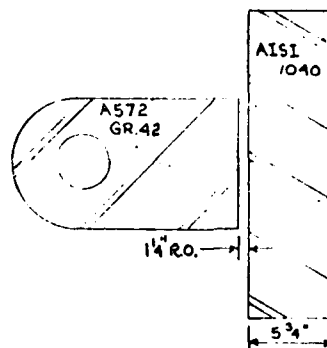
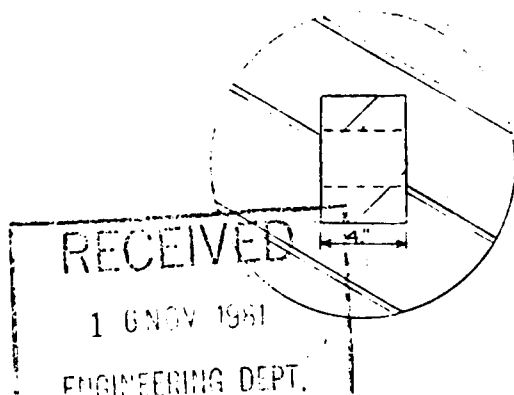
ENGINEERING DEPT.

Enclosure

2-71

Company Name Bethlehem Steel CorporationProcedure Qualification Record No. 333Date 11 September 81WPS No. 333Welding Process(es) E.S.W.Types (Manual, Automatic, Semi-Auto.) Auto

## JOINTS (QW-402)



Groove Design Used

## BASE METALS (QW-403)

Material Spec. A572 to AISI 1040Type or Grade GR. 42P No. 1 to P No. 1Thickness 4" to 5-3/4"Diameter N.A.

Other \_\_\_\_\_

## POSTWELD HEAT TREATMENT (QW-407)

Temperature 1625 - 1650°FTime 1/2 Hr./In. Max.

Other \_\_\_\_\_

## GAS (QW-403)

Type of Gas or Gases N.A.

Composition of Gas Mixture \_\_\_\_\_

Other \_\_\_\_\_

## FILLER METALS (QW-404)

Weld Metal Analysis A No. 1Size of Electrode 1/8"Filler Metal F No. 6SFA Specification 5.17 - 80AWS Classification E7A2 - EH14

Other \_\_\_\_\_

## ELECTRICAL CHARACTERISTICS (QW-403)

Current DirectPolarity ReverseAmps. 700 Volts 45

Other \_\_\_\_\_

## POSITION (QW-405)

Position of Groove 3GWeld Progression (Uphill, Downhill) Uphill

Other \_\_\_\_\_

## TECHNIQUE (QW-410)

Travel Speed 0.29 IPMString or Weave Bead WeaveOscillation 48/Min. Avg.Multipass or Single Pass (per side) SingleSingle or Multiple Electrodes Single

Other \_\_\_\_\_

## PREHEAT (QW-406)

Preheat Temp. 32°F Min. 150-250°F optionalInterpass Temp. N.A.

Other \_\_\_\_\_

**QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATION (WPS)**  
(See QW-201.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name Bethlehem Steel Corporation By: J.C. West - J.A. Hyatt  
Welding Procedure Specification No. 333 Date 11 Sept 81 Supporting PQR No.(s) 333  
Revision No. \_\_\_\_\_ Date \_\_\_\_\_  
Welding Process(es) E.S.W. Type(s) Auto  
(Automatic, Manual, Machine, or Semi-Auto.)

**JOINTS (QW-402)**

Joint Design Square Groove "Tee" Joint

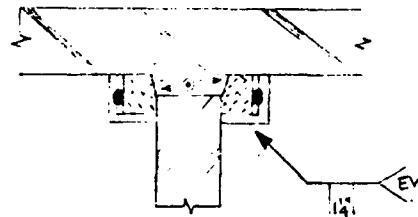
Backing (Yes) X (No) \_\_\_\_\_

Backing Material (Type) Copper Molding Shoe

Sketches, Production Drawings, Weld Symbols or Written Description should show the general arrangement of the parts to be welded. Where applicable, the root spacing and the details of weld groove may be specified.

(At the option of the Mfr., sketches may be attached to illustrate joint design, weld layers and bead sequence, e.g. for notch toughness procedures, for multiple process procedures, etc.)

**Details**



**\*BASE METALS (QW-403)**

P-No. 1 Group No. 1 to P-No. 1 Group No. 2

OR

Specification type and grade A572 GR. 42

to Specification type and grade AISI 1040

OR

Chem. Analysis and Mech. Prop. \_\_\_\_\_

to Chem. Analysis and Mech. Prop. \_\_\_\_\_

Thickness Range:

Base Metal: Groove 0.5 - 1.1 T Fillet N.A.

Deposited Weld Metal \_\_\_\_\_

Pipe Dia. Range: Groove N.A. Fillet N.A.

Other \_\_\_\_\_

**\*FILLER METALS (QW-404)**

F-No. 6 Other \_\_\_\_\_

A-No. 1 Other \_\_\_\_\_

Spec. No. (SFA) 5.17 - 80

AWS No. (Class) F7A2 - EH14

Size of filler metals 1/8" Linde 36

5/8" Linde mild steel consumable guide #896 F2T Type S

(Electrode, Cold Wire, Hot Wire, etc.)

Electrode-Flux (Class) F7A2 - EH14

Flux Trade Name Linde 124

Consumable Insert \_\_\_\_\_

\*Each base metal-filler metal combination should be recorded individually.

## QW-482 (Back)

<b>POSITIONS (QW-405)</b> Position(s) of Groove <u>3G</u> Welding Progression: Up <u>X</u> Down _____ Position(s) of Fillet <u>N.A.</u>	<b>POSTWELD HEAT TREATMENT (QW-407)</b> Temperature Range <u>1625 - 1650</u> °F Time Range <u>1/2 Hr./In.</u> Max.
<b>PREHEAT (QW-406)</b> Preheat Temp. Min. <u>32</u> °F Interpass Temp. Max. <u>N.A.</u> Preheat Maintenance _____ (Continuous or special heating where applicable should be recorded)	<b>GAS (QW-408)</b> Shielding Gas(es) <u>N.A.</u> Percent Composition (mixtures) _____ Flow Rate _____ Gas Backing _____ Trailing Shielding Gas Composition _____

**ELECTRICAL CHARACTERISTICS (QW-409)**

Current AC or DC D.C. Polarity R.P.  
 Amps (Range) 560-840 Volts (Range) 40-55  
 (Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)  
 Tungsten Electrode Size and Type N.A. (Pure Tungsten, 2% Thoriated, etc.)  
 Mode of Metal Transfer for GMAW N.A. (Spray arc, short circuiting arc, etc.)  
 Electrode Wire feed speed range 110 - 200 IPM 130 Avg.

**TECHNIQUE (QW-410)**

String or Weave Bead Weave  
 Orifice or Gas Cup Size N.A.  
 Initial and Interpass Cleaning (Brushing, Grinding, etc.) Manual brushing or grinding of abutting edges prior to welding.  
 Method of Back Gouging Air carbon - Arc  
 Oscillation 48/Min.  
 Contact Tube to Work Distance N.A.  
 Multiple or Single Pass (per side) Single  
 Multiple or Single Electrodes Single  
 Travel Speed (Range) 0.18 - 0.4 IPM  
 Peening N.A.  
 Other \_\_\_\_\_

Pass no.	Electrode size	Welding current		Joint detail
		Amperes	Volts	
1	1/8"	700	45	
Guide tube flux <u>Linde 124</u> Guide tube composition <u>Mild steel</u> Guide tube diameter <u>5/8"</u> Vertical rise speed <u>0.29 IPM</u> Traverse length <u>4"</u> Traverse speed <u>3.2 I.P.S.</u> Dwell <u>None</u> Type of molding shoe <u>Fixed Cu. Shoe</u>				



# SOUTHWESTERN LABORATORIES

## REPORT OF TESTS ON METAL SPECIMENS

FILE NO. 4092300

Beaumont

TEXAS October 19, 1981

TO: Bethlehem Steel Corporation

REPORT NO. 96577-cp

PROJECT Mechanical Testing

ORDER NO. X-1550-102-9518A  
c/o#9

MATERIAL A-572 to AISI 1040

IDENTIFICATION WPS 333

SPEC. REFERENCE ASME Sec. IX

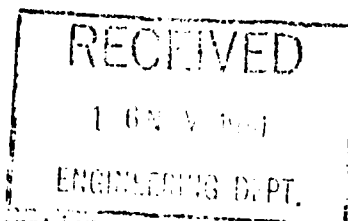
Specimen	Size	Sq. In. Area	Yield, p.s.i.*	Ultimate Strength, lbs.	Tensile Strength, p.s.i.	% El.	% R.A.	Location of Fracture
----------	------	--------------	----------------	-------------------------	--------------------------	-------	--------	----------------------

### REQUIRED:

T1A	1.074 x .946	1.016	48,228	74,000	72,834			Parent Metal
T1B	1.076 x .942	1.013	47,384	76,000	75,024			Parent Metal
T1C	1.070 x .856	.9159	45,856	70,000	76,427			Weld Metal
T1D	1.090 x .975	1.062	45,197	76,500	72,033			Parent Metal
T2A	1.054 x .942	.9928	46,333	72,000	72,522			Parent Metal
T2B	1.079 x .831	.8966	45,728	67,000	74,726			Weld Metal
T2C	1.071 x .998	1.068	44,007	80,000	74,906			Weld Metal
T2D	1.056 x .931	.9831	43,739	72,500	73,746			Weld Metal

Side Bend 1A	Satisfactory			Yield, psi	Tensile Strength, psi
2A	Satisfactory				
3A	Satisfactory	T1 Average	46,666		74,079
4A	Satisfactory	T2 Average	44,951		73,975

Side Bend 1B	Satisfactory
2B	Satisfactory
3B	Satisfactory
4B	Satisfactory



TECHNICIAN: J. Blair

COPIES TO: 3-Bethlehem Steel Corporation  
Attn: Jim Hyatt

SOUTHWESTERN LABORATORIES

2-75

*John P. Chivers*

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## SOUTHWESTERN LABORATORIES

## REPORT OF TESTS ON METAL SPECIMENS

FILE NO. 4092300

Beaumont

TEXAS October 19, 1981

TO: Bethlehem Steel Corporation

REPORT NO. 96651-cp

PROJECT Mechanical Testing

ORDER NO. X-1550-102-9518A

MATERIAL A-572 to AISI 1040

c/o #9

IDENTIFICATION WPS 333


SPEC. REFERENCE ASME Sec. IX

Specimen	Size	Sq. In. Area	Yield, p.s.i.*	Ultimate Strength, lbs.	Tensile Strength, p.s.i.	% El.	% R.A.	Location of Fracture
----------	------	-----------------	----------------	----------------------------	-----------------------------	-------	--------	----------------------

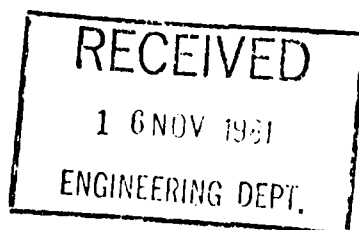
## REQUIRED:

T1 .501" Dia. .1963 56,036 16,000 81,507 34% 64.9

1-Macro-Etch specimen before normalization - Satisfactory

1-Macro-Etch specimen ~~before~~ normalization - SatisfactoryAFTER 

Testing witnessed by: S.E. Rush - ABS



TECHNICIAN: John Blair

COPIES TO: 3-Bethlehem Steel Corporation

Attn: Jim Hyatt

SOUTHWESTERN LABORATORIES

2-76

# SOUTHWESTERN LABORATORIES

FORT WORTH DALLAS HOUSTON MIDLAND BEAUMONT TEXARKANA

File No. 4092300

Beaumont

Texas, October 19, 1981

## IMPACT TESTS ON STEEL

To Bethlehem Steel Corporation  
P.O. No. X-1550-102-9518A c/o#9 Date of Test 10-7-81  
Material A-572 to AISI-1040  
Identification Marks WPS 333  
Specifications ASME SA-370

Testing Machine: T.O. Ser.# 84440 Test Method: "V" Notch Simple Beam Charpy  
Linear Velocity of Hammer: 16.8 ft. per second  
Effective Energy: 264 ft. pounds Specimen Type: "A"  
Specimen Size: 10mm x 10mm Specimen Temp: Plus 32° F

Specimen Identification	Width	Effective Section Size	Impact Value Ft. Lbs.	Lateral Exp. Mills	% Shear
Weld #1	.394	.315	62.0	40.0	10
Weld #2	.394	.314	59.0	38.0	10
Weld #3	.394	.315	49.0	22.0	10

RECEIVED

16 NOV 1981

ENGINEERING DEPT.

Copies: 3--Bethlehem Steel Corporation  
Attn: Jim Hyatt

SOUTHWESTERN LABORATORIES

PER

*Jack R. Turner*

Lab. No. 96652-cp

2-77

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# SOUTHWESTERN LABORATORIES

FORT WORTH DALLAS HOUSTON MIDLAND BEAUMONT TEXARKANA

FILE No. 4092300

Beaumont

TEXAS, October 19, 1981

## IMPACT TESTS ON STEEL

To Bethlehem Steel Corporation  
P. O. No. X-1550-102-9518A c/o #9 Date of Test 10-7-81  
Material A-572 to AISI-1040  
Identification Marks WPS 333  
Specifications ASME SA-370

Testing Machine: T.O. Ser. #88440 Test Method: "V" Notch Simple Beam Charpy  
Linear Velocity of Hammer: 16.8 ft. per second  
Effective Energy: 264 ft. pounds Specimen Type: "A"  
Specimen Size: 10mm x 10mm Specimen Temp: Plus 32° F

<u>Specimen Identification</u>	<u>Width</u>	<u>Effective Section Size</u>	<u>Impact Value Ft. Lbs.</u>	<u>Lateral Exp. Mills</u>	<u>% Shear</u>
1040 #1	.394	.315	22.0	12.0	5
1040 #2	.394	.315	15.0	7.0	5
1040 #3	.394	.315	13.0	8.0	5
A-572 #1	.394	.315	231.0	62.0	5
A-572 #2	.394	.314	177.0	80.0	5
A-572 #3	.394	.314	20.0	10.0	5

Copies: 3-Bethlehem Steel Corporation  
Attn: Jim Hyatt

SOUTHWESTERN LABORATORIES

PER

*Jack B. Turner*

Lab. No. 96672-cp

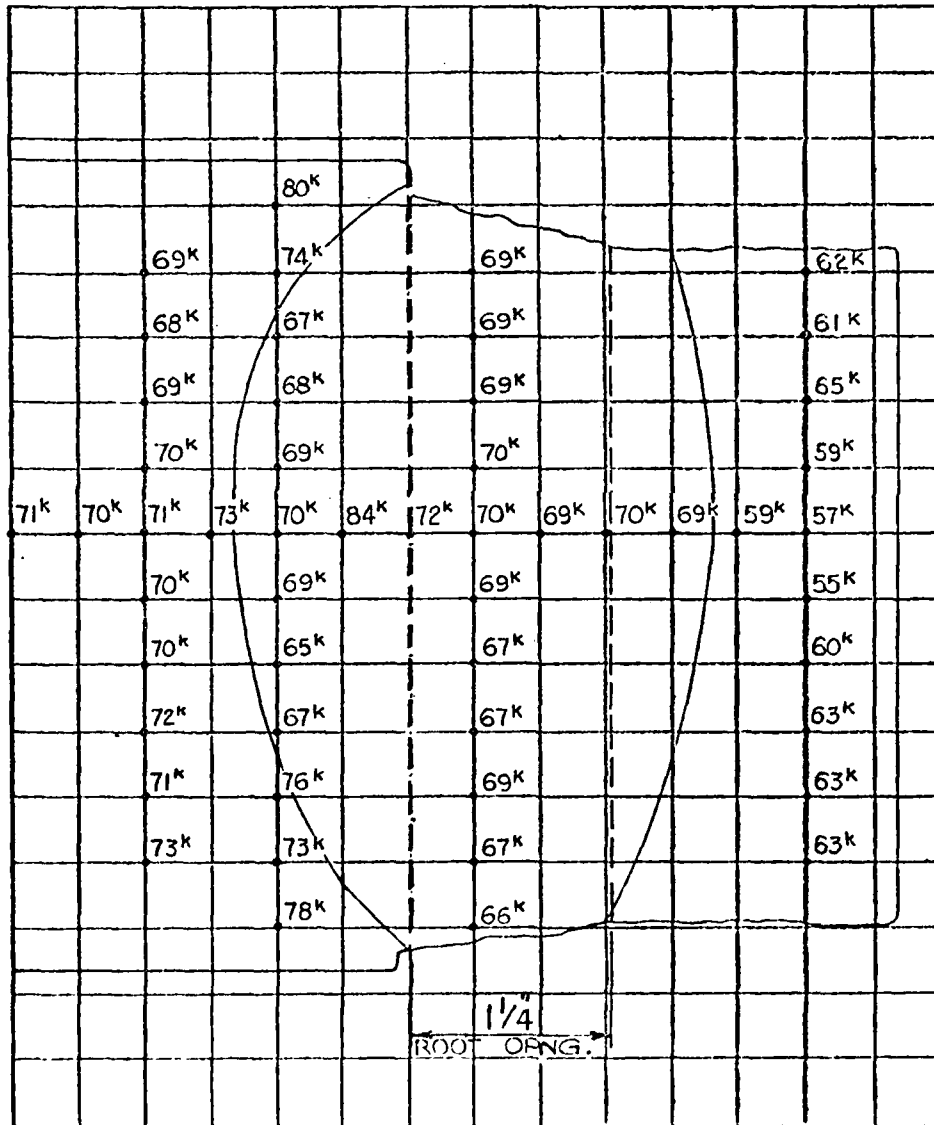
2-78

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# WELD PROCEDURE 333

PLATE I.D. NORMALIZED

## ROCKWELL B SCALE



% DILUTION  
= 50 %

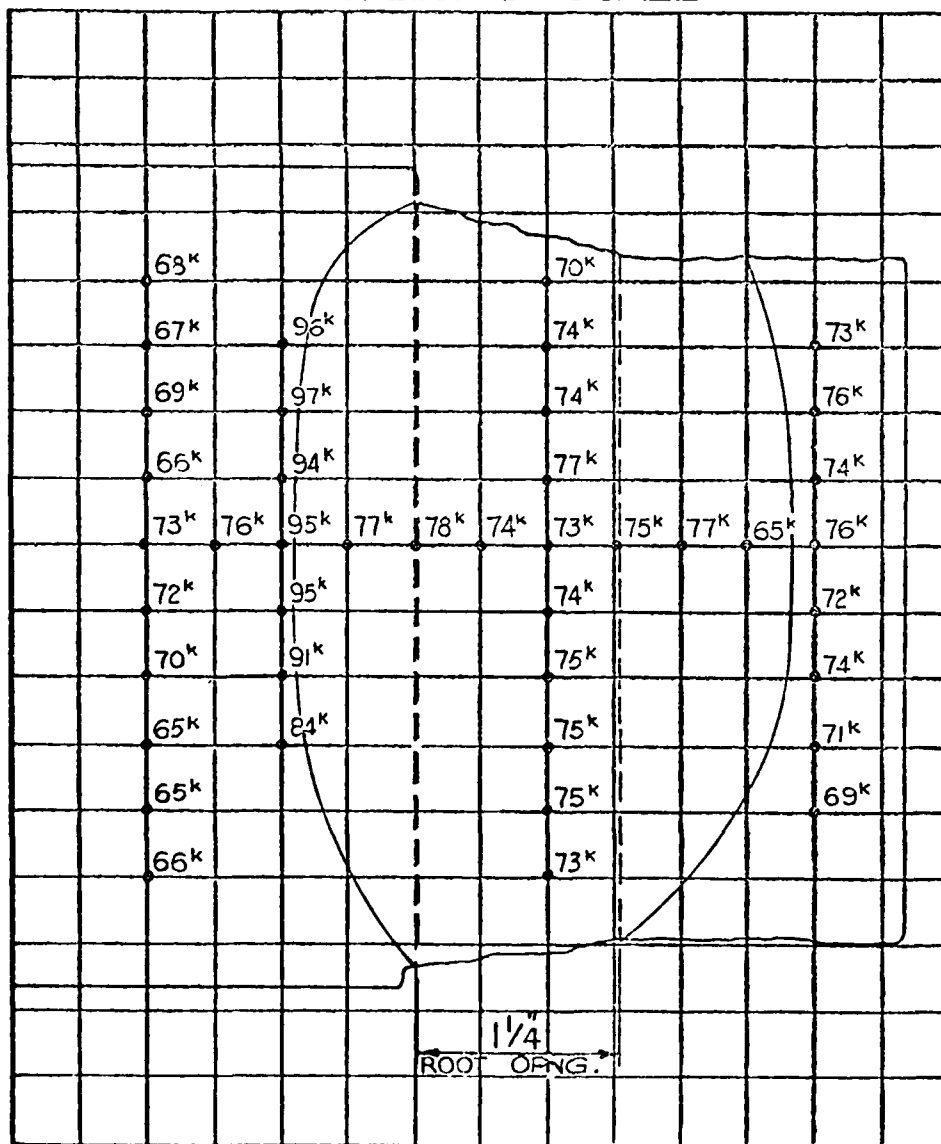
SCALE 1 SQUARE = 1 CM

BETHLEHEM STEEL  
BEAUMONT, TEX.

# WELD PROCEDURE 333

PLATE I.D. UNNORMALIZED

ROCKWELL B SCALE



% DILUTION  
= 50 %

SCALE 1 SQUARE = 1 CM

2-80

BETHLEHEM STEEL  
BEAUMONT, TEX.



SESSION II

ELECTROSLAG WELDING OF  
NONFERROUS ALLOYS/  
ELECTROSLAG CASTING



ELECTROSLAG WELDING OF NON-FERROUS METALS--

A Review

by

Jack H. Devletian, Ph.D.  
Associate Professor  
Department of Materials Science and Engineering

Oregon Graduate Center  
19600 N.W. Von Neumann Drive  
Beaverton, Oregon 97006-1999

May 24, 1985

## ABSTRACT

A critical review of the electroslog welding (ESW) of non-ferrous metals literature has revealed that Ti, Al, Cu and Ni alloys are most commonly welded in the Soviet Union. Oxygen-free halide fluxes are required for ES welding reactive alloys of Ti and Al for structural applications, high purity Cu and Al for buss bars, and superalloys of Ni containing reactive metal additions. The common problem associated with ESW these metals is the poor ohmic heating provided by the excessively conductive ( $\approx 7 \Omega^{-1} \text{cm}^{-1}$  at  $1700^\circ\text{C}$ ) fluoride or chloride-based slags. Ion complexing of the slag appears to be the most promising method of improving the slag's poor heating efficiency. Nevertheless, the inadequate slag heating is overcome by the development of optimum welding conditions to deposit fully-fused welds. These conditions include the utilization of plate and nozzle guides (for consumable guide ESW) and multiple large diameter filler wires (for non-consumable ESW). At present, the Soviet Union is the clear leader in the ESW of non-ferrous metals although a great deal of flux development and process improvement work is still needed.

## INTRODUCTION

Since its inception in the early 1950's, electroslag welding (ESW) has established itself as the most cost-effective method of joining thick section plate. Its commercial success has been largely built upon the joining of steel and stainless steel. Of the many commercially important non-ferrous metals, only Ti, Al, Cu and Ni alloys have been reported extensively in the ESW literature primarily from the Soviet Union. Ti alloys and, to a lesser extent, Al alloys are welded by ESW for structural application while pure Al and Cu are welded for the fabrication of buss bars and large electrical conductors. Ni alloys are occasionally joined by ESW, but most recently are deposited as electroslag cladding over other metal substrates.

## LITERATURE ASSESSMENT

### Parent Metal Properties Affecting ESW

Due to their unique physical properties, Ti, Al and Cu are difficult to weld by ESW. Ti and Al are extremely reactive and must only be welded with oxygen-free halide slags which are inefficient sources of ohmic heating. Though Cu is not as reactive, it too must be welded with halide fluxes to ensure OFHC electrical quality. Because of their high values of thermal diffusivity, both Cu and Al (see Table I) require maximum heating efficiency during ESW to develop adequate side wall fusion. Schematically from Figure 1, the ESW parameters to join heavy section Ti, Al or Cu must be optimized to achieve maximum side wall penetration to overcome the poor ohmic heating of fluoride and chloride slags. The high resistivity (Figure 2) and melting temperature (Table I) of Ti present further complications because of the tendency of Ti filler metal to "burn back" uncontrollably due to  $I^2R$  heating. Thus, unusually large diameter electrodes with short electrical stickouts are required for non-consumable guide ESW of Ti while plate electrodes or nozzle electrodes are needed for consumable guide ESW. Perhaps the most serious problems preventing the general ESW of Al are low density and low melting temperature. Very few flux ingredients have melting points and densities below those of Al. If a comparison is drawn between the densities of Al and a few common flux ingredients (see Figure 3), the choices for fluxes for ESW Al are very limited. Ni can be welded with mixtures of  $\text{CaF}_2$ - $\text{CaO}$ - $\text{Al}_2\text{O}_3$  which provide excellent ohmic heating for ESW. However, as the amounts of reactive alloying elements (Ti, Zr, Al, etc.) increase, the percentage of CaF and halide ingredients must also increase to prevent oxidation of the reactive elements.

## Halide Fluxes

The properties of slags for ESW of non-ferrous metals must possess the appropriate properties listed in Table II. Although halide slags are virtually oxygen free and chemically stable, their high electrical conductivities provide poor ohmic heating and inadequate viscosity for practical ESW. For example, the electrical conductivity of  $\text{CaF}_2$  at  $1700^\circ\text{C}$  is  $7 \Omega^{-1} \text{cm}^{-1}$  (Figure 4), which is more than twice that needed for efficient ohmic heating. Fluxes for ESW Ti must have sufficiently high melting ranges to avoid slag volatilization while fluxes for Al must have a lower melting temperature and density than Al. A current listing of Soviet fluxes for Ti and Al are presented in Tables III and IV, respectively. The "gettering" action of the slag is desirable for ESW but difficult to realize in Ti and Al welds. To a first approximation, the Gibbs free energy of formation of impurity interstitial compounds formed by the getters must be more negative than those formed by Ti or Al. For example, Figure 5 illustrates the stability of impurity oxides of Y, La and Ce.

## Ion Complexing and Optimizing Welding Parameters

The problem of producing sufficient ohmic heating of the slag to achieve fully-fused welds may have been partially overcome by researchers in the Soviet Union by (1) alloying the slag to develop large immobile ion complexes to reduce conductivity (while increasing viscosity), and (2) optimizing welding parameters for ESW to obtain maximum slag heating. From Table V, if  $\text{YF}_3$  is added to a  $\text{CaF}_2$ -base slag, large complex ions such as  $[\text{YF}_6]^{3-}$  replace numerous smaller  $\text{Y}^{3+}$  and  $\text{F}^-$  ions to substantially reduce electrical conductivity of slag as illustrated in Figure 6. Many Soviet fluxes (ANT14, ANA301, and ANA302) in Tables III and IV used to weld Ti and

Al are secret, but are believed to have achieved sufficient complexing to reducing slag conductivity for more efficient slag heating. Nevertheless, the constant utilization of large diameter electrodes and plate/nozzle electrodes and even preheating indicate that the Soviet fluxes may still be inadequate for routine ESW as is performed on steel with oxide fluxes. As a result, plate electrodes (Figure 7a), web-type nozzle electrodes (Figure 8) with argon lancing to reduce interstitial impurities (Figure 9) are used in consumable guide ESW to greatly reduce current density and increase heating efficiency without arcing. In non-consumable guide ESW, multiple and large diameter ( $\approx 5\text{mm}$ ) electrodes must be used to achieve good weldability (Figures 7b and 10).

#### Weldability of Ti, Al, Cu and Ni Alloys

The specific problems associated with each alloy type: (1) Ti, (2) Al, (3) Cu, and (4) Ni alloys are summarized in Table VI, which is based on the technical literature primarily from the Soviet Union. The high resistivity of Ti promotes rapid  $I^2R$  heating of the Ti consumables. Thus, a short dry stickout (Figure 11) and a large diameter (5mm) electrode for non-consumable guide ESW (Table VII) and a short consumable nozzle depending upon welding current (Figure 12) or plate guide (Figure 7a). The slag components (Table III) must be chemically stable to prevent molten Ti from either reacting with the slag unfavorably or absorbing interstitial impurities from the slag. To ensure freedom from interstitial contamination, the Soviets cover all hot portions of the weld joint with an argon blanket. Argon lancing has also been used to purge the weld pool of impurities (Figure 9). The use of getters may also be used to cleanse the weld

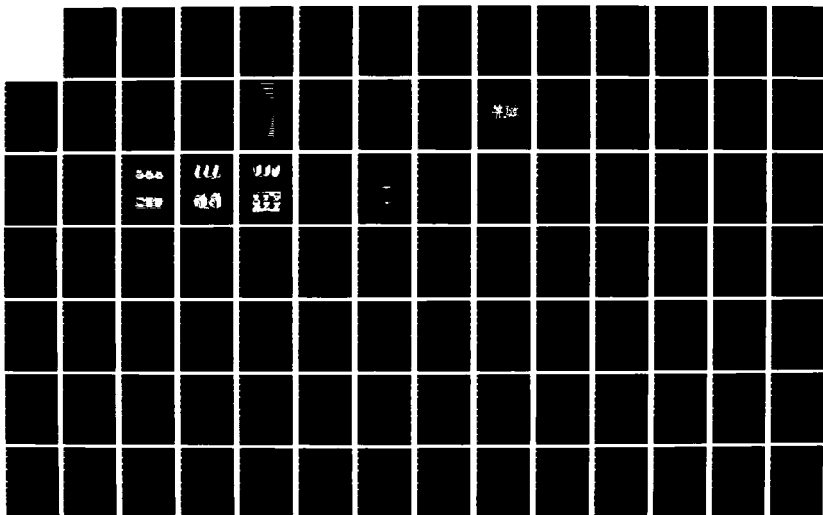
AD-A166 926

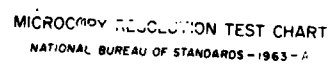
ELECTROSLAG PROCESSING FOR MARINE APPLICATION SUMMARY  
REPORT ON A WORKSHOP (U) NAVAL ACADEMY ANNAPOLIS MD DIV  
OF ENGINEERING AND WEAPONS W A PALKO ET AL. MAR 85  
EW-20-85 F/G 13/8

2/3

UNCLASSIFIED

NL





MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A



as well as decrease slag conductivity. Welds are normally deposited without preheating using typical parameters given in Table VII.

Aluminum is perhaps most difficult to weld by ESW primarily because there are so few chemically stable fluxes that have both lower melting temperature and lower density than aluminum. Most fluxes are based on NaCl (see Table IV). The confidential fluxes ANA301, ANA302 and "autogal" are claimed to achieve excellent welds. Based on observed microstructures of Soviet welds, slag inclusion and lack of fusion are commonly encountered defects which indicate that Al is still extremely difficult to weld even with plate electrodes and preheating.

Cu alloys are welded by ESW (Table VIII) using preheating and  $\text{CaF}_2$  based slags that contain a small percentage of oxide component for effective ion complexing. However, if pure Cu is welded, greater preheating temperatures and plate electrodes are recommended since only fluoride fluxes can be used to maintain OFHC quality. Graphite molds are also needed to prevent the great extraction of ohmic heat by the water-cooled copper molds.

Ni alloys are the simplest (of those previously discussed) to weld since  $\text{CaF}_2\text{-Al}_2\text{O}_3\text{-CaO}$  fluxes can be used. However, as the quantity of reactive metal increases in the Ni alloy, the need for lower oxygen potential slags increases up to the point where only a fluoride slag is required to prevent the oxidation of reactive elements in the weld. The utilization of pure Ni as a thick clad is gaining popularity (Figure 13) and it is deposited by electroslog cladding using efficient oxide-based fluxes.

## CONCLUSIONS

The Soviet Union is the clear leader in the ESW of non-ferrous metals. Based on an assessment of the available ESW literature, the following are concluded.

1. Ti and Al alloys have been successfully joined by ESW using fluoride/chloride flux mixtures and welding procedures utilizing large diameter electrodes (for non-consumable guide ESW) and plate guide or nozzles (for consumable guide ESW) to compensate for the poor ohmic heating of halide slags.
2. High purity Cu and Al buss bars are also joined by ESW using fluoride/chloride fluxes to maintain OFHC quality. Due to the large values of thermal diffusivity, welds are often preheated to achieve adequate sidewall fusion.
3. Ni alloys are as simple to join by ESW as stainless steel using fluxes containing  $\text{CaF}_2$  and oxides for efficient ohmic slag heating. However, as the reactive metal content of the Ni alloy increases, the need to use all fluoride/chloride fluxes also increases.

## GENERAL REFERENCES

1. Wheatley, J. M., "Welding Thick Aluminum--A Literature Survey", Australian Welding Res., Vol. 8 (2), 1980, p. 30.
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TABLE I.  
PHYSICAL PROPERTIES OF METALS

	THERMAL DIFFUSIVITY MM <sup>2</sup> /S	MELTING TEMPERATURE, °C	MINIMUM HEAT INPUT TO MELT KJ/G
TITANIUM	9.0	<u>1672</u>	<u>1.8</u>
NICKEL	4.7	1455	1.3
ALUMINUM	<u>92.0</u>	<u>660</u>	1.4
COPPER	<u>96.0</u>	1085	0.9
STEEL (REFERENCE)	9.1	1510	1.7

TABLE II.  
PROPERTIES OF ESW FLUXES

1. EFFICIENT  $I^2R$  HEATING
2. ELECTRICAL RESISTANCE
3. ADEQUATE VISCOSITY
4. CHEMICAL AND THERMAL STABILITY
5. MELTING TEMPERATURE
6. DENSITY
7. "GETTER" ACTION
8. SURFACE TENSION

TABLE III.  
LISTING OF SOVIET FLUXES USED FOR WELDING TITANIUM ALLOYS (U)

UNCLASSIFIED	
Flux Designation	Probable Composition
AN-T1 AN-T2	CaF <sub>2</sub> -LiF base pure CaF <sub>2</sub>
AN-T3 AN-T4	SrF <sub>2</sub> -LiF base SrF <sub>2</sub> -LiF eutectic
AN-T5 AN-T7	-- --
AN-T11	93%[CaF <sub>2</sub> -1%NaF] + 7%[SrF <sub>2</sub> -SrCl <sub>2</sub> ]
AN-T13 AN-T14	-- --
AN-T19A	--
U.S. Patent 3,551,218	77.5-94.5% CaF <sub>2</sub> 0.5-1.5% NaF 5.0-21.0% BaCl <sub>2</sub>
U.S. Patent 3,849,211	83-92% CaF <sub>2</sub> 3-7% BaF <sub>2</sub> 5-10% AlF <sub>3</sub>
USSR Inventor's Certificate No. 348314	58-66% CaF <sub>2</sub> 34-42% AlF <sub>3</sub>

\*The SrF<sub>2</sub>-LiF eutectic is approximately 65%SrF<sub>2</sub>-35%LiF.



TABLE IV.  
FLUXES FOR ESW OF AL ALLOYS

COMPONENTS AND CONSTITUENTS OF FLUXES FOR ELECTROSLAG WELDING OF ALUMINIUM

Author reference	I		Po			B	Pa	E	
	ANA1	ANA301 ANA302	A	B	C			A	B
Cryolite	30	—	—	—	—	—	—	—	—
NaCl	20	—	50	50	50	85	—	50	—
KCl	50	—	—	—	—	8	80	—	30
SiO <sub>2</sub>	—	—	—	—	—	4	—	—	—
CaF <sub>2</sub>	—	—	—	—	—	2	—	—	—
LiF	—	—	—	25	25	—	—	25	30
NaF	—	—	—	25	—	—	20	25	—
KF	—	—	—	—	25	—	—	—	—
Autogal	—	—	50	—	—	—	—	—	—
MgCl <sub>2</sub>	—	—	—	—	—	—	—	—	30
MgF <sub>2</sub>	—	—	—	—	—	—	—	—	10

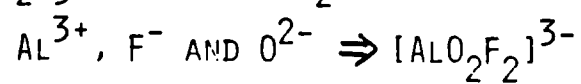
I Ischenko  
Po Potthoff  
B Boizeau  
Pa Patchett (ingots only)  
E Eichhorn

WELDING CONDITIONS – ELECTROSLAG SYSTEMS

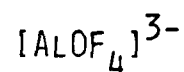
Author	Work	Flux	Mould	Current	Volts	Electrode	Preheat
Ischenko 1966, b	Ingots 140mm dia.	ANA1	Water-cooled Steel	1300-1800A (AC)	25-31	60mm dia. bar	
Potthoff 1973	Ingots	NaCl + Autogal or NaCl/NaF/ LiF/KF	Water-cooled copper	250A 700A	— 32	2.4mm wire 5mm wire	
	Welding 30mm thick plate	NaCl + Autogal	graphite plates	600-700A (DC + ve)	34-36	5mm wire copper tube	Preheat 250°C
	30mm plate			1600A (AC)	33	7mm wire Al. consumable guide	Preheat 120°C
	30mm plate	NaCl + Autogal	graphite plates	600-700 (DC + ve)	35	5mm Al. guide tube 10x1.5mm	Preheat 250°C
Boizeau 1974, c	40mm plate	NaCl 40 KCl 10 SiO <sub>2</sub> 5 CaF <sub>2</sub> 2.5	graphite steel backed water-cooled	more than 1500A (AC)	less than 37	3x5mm wire consumable guide	Preheat 150- 180°C or less
Eichhorn 1975/76	45mm plate	30% KCl 30% MgCl <sub>2</sub> 30% LiF 10% MgF <sub>2</sub>	water-cooled copper sliding shoes or multi layer carbon mats	1000- 1100A (AC)	32	2x4.4mm wires through nozzles	

TABLE V.  
ION COMPLEXING REACTIONS

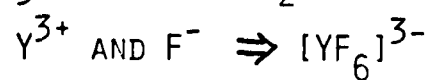
1.  $\text{Al}_2\text{O}_3$  ADDED TO  $\text{CaF}_2$  BASE:



OR



2.  $\text{YF}_3$  ADDED TO  $\text{CaF}_2$  BASE:



OR

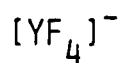


TABLE VI.  
SUMMARY OF PROBLEMS ASSOCIATED WITH ESW OF  
NON-FERROUS METALS

PROBLEMS IN ESW OF TITANIUM

1. HIGH RESISTIVITY OF TI
2. HIGH REACTIVITY OF TI
3. POOR OHMIC HEATING OF FLUORIDE AND CHLORIDE SLAGS
4. INTERSTITIAL CONTAMINATION

PROBLEMS IN ESW OF ALUMINUM

1. LOW MELTING POINT LIMITS SELECTION FOR FLUX
2. LOW DENSITY LIMITS SELECTION FOR FLUX
3. SLAG IS CHEMICALLY UNSTABLE
4. HIGH  $\alpha$  AND K LIMIT EFFICIENT HEATING
5. GRAPHITE MOLDS OFTEN USED

TABLE VI. (CONT.)  
SUMMARY OF PROBLEMS ASSOCIATED WITH ESW OF  
NON-FERROUS METALS

PROBLEMS WITH ESW COPPER

1. OXIDE FLUXES CAN BE USED
2. OFHC QUALITY REQUIRES FLUORIDE FLUXES
3. HIGH  $\alpha$
4. GRAPHITE MOLDS

PROBLEMS WITH ESW NICKEL

1. NONE, OXIDE FLUXES CAN BE USED
2. ALLOYS CONTAINING AL, TI, CR, ETC. REQUIRE FLUORIDE-RICH FLUXES

TABLE VII.

## CONVENTIONAL ESW OF SOVIET ALLOY VT1 WITH A SINGLE ELECTRODE

Plate Thickness	40-50 mm (1.6"-2.0")
Joint Gap	25-28 mm
Flux	ANT-2 (pure $\text{CaF}_2$ )
Power Supply	a-c
Current	500-600 amps
Voltage	22-24 V
Electrode Feed Rate	200 m/hr (131 in/min)
Slag Pool Depth	30-35 mm (1.2"-1.4")
Electrode Diameter	5 mm ( $>3/16"$ )

## CONVENTIONAL ESW OF VT1 TITANIUM WITH MULTIPLE ELECTRODES

Slab Thickness mm	No. of Electrodes	Welding Gap mm	UNCLASSIFIED	
			Voltage	Current amps
40	1	30-32	28-30	680-1350
70	1	30-32	32-35	680-1350
100	2	32-34	28-30	1360-2700
150	2	32-34	32-35	1360-2700

Note: Electrode Stickout--50-70 mm; Slag Pool Depth--30-40 mm;  
Plate--VT1; Wire--VT1; Wire Diameter--5 mm; Flux--ANT-4.

## TABLE VIII.

## ESW COPPER

## FLUXES:

NAF 50-67% (BRITISH PATENT 1399712)

LIF 18-20%

CAF<sub>2</sub> 7-14%

SiO<sub>2</sub> 6-10%

TI, NB OR ZR METAL

OTHER FLUXES: AN-8, AN-348A

SHOES: GRAPHITE

VOLTAGE: 30V MAXIMUM

CURRENT:  $f$  (THICKNESS)

## TYPICAL MECHANICAL PROPERTIES

	<u>BASE METAL</u>	<u>WELD</u>
$\sigma_T$	26 KSI	25 KSI
$\sigma_Y$	13 KSI	12.6 KSI
%E	46	44

CRACK FREE--SLAG FREE

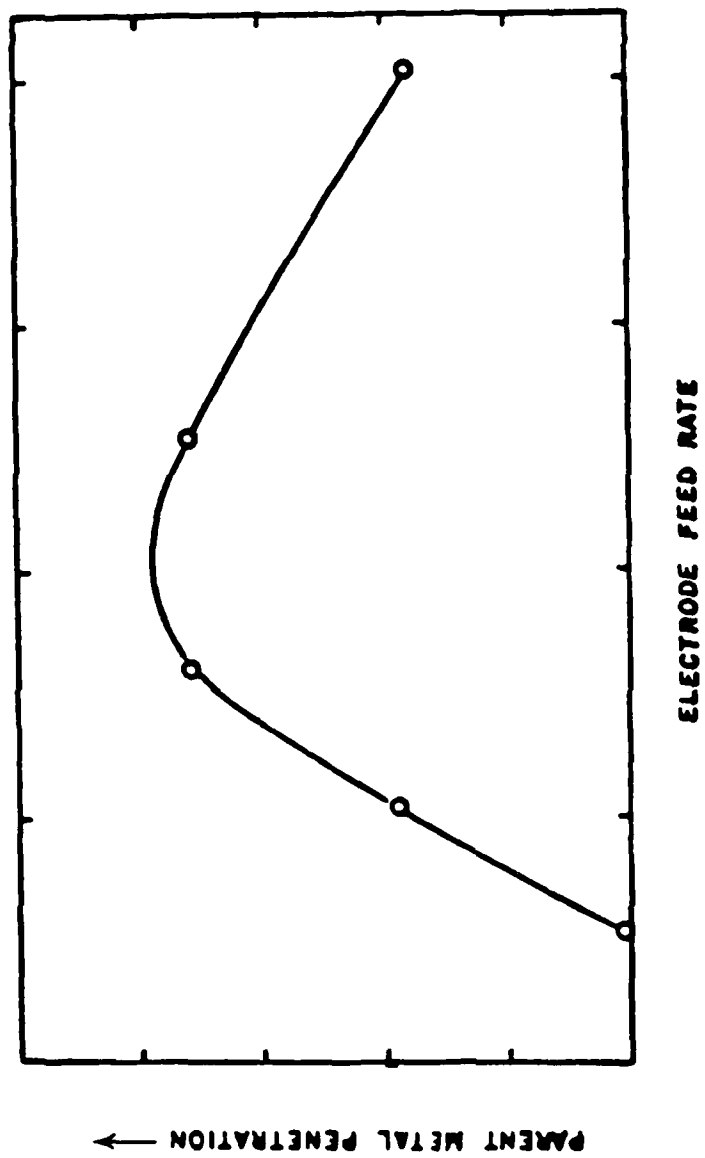
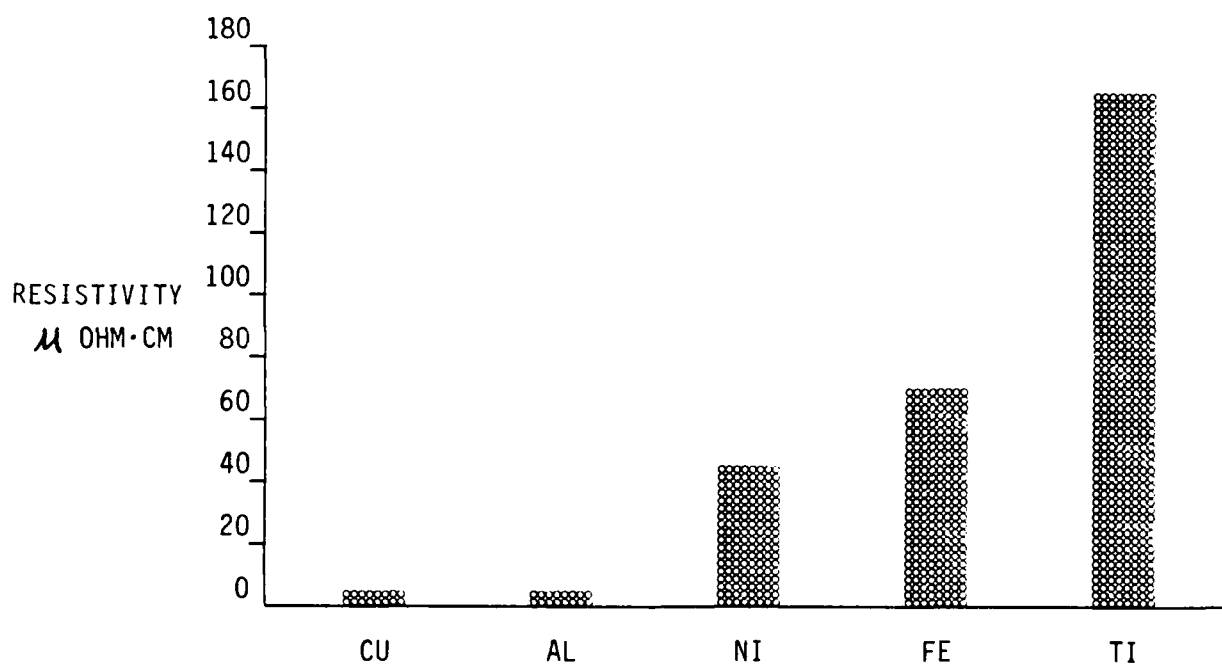


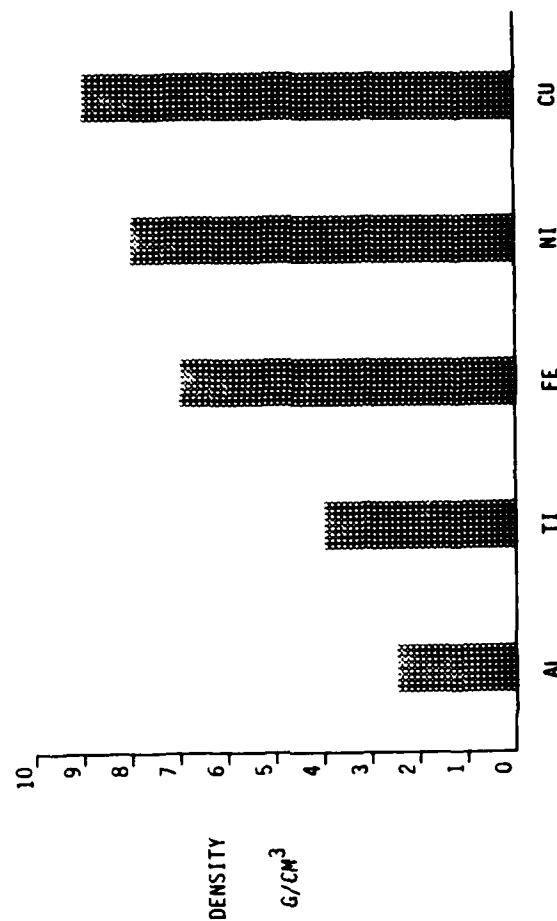
FIGURE 1. PENETRATION VS. ELECTRODE FEED RATE IN ESW

FIGURE 2.  
RESISTIVITY AT  $\frac{1}{2} T_M$





DENSITY OF METAL AT 25°C



DENSITY OF FLUX AT 25°C

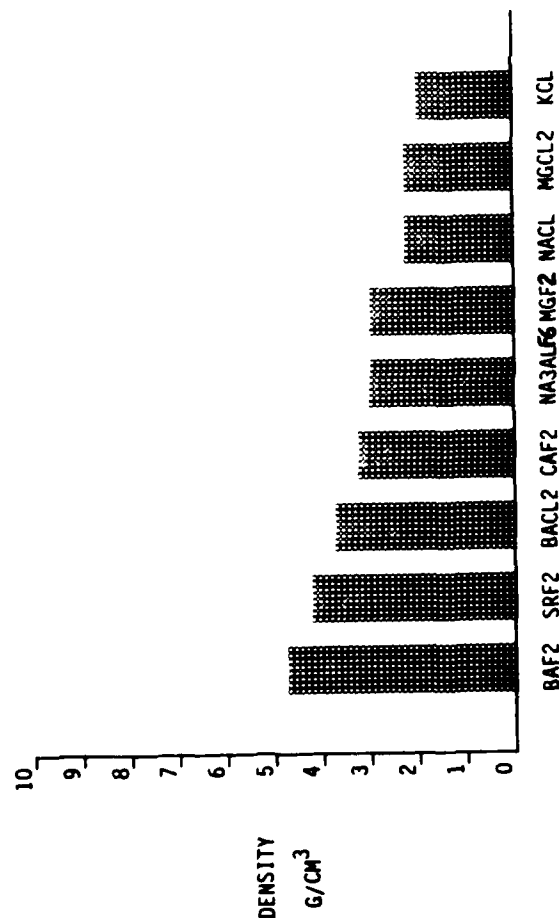


FIGURE 3. DENSITY COMPARISON BETWEEN FLUX COMPONENTS AND METALS COMMONLY WELDED BY ESW.

FIGURE 4.  
ELECTRICAL CONDUCTIVITY OF SLAGS

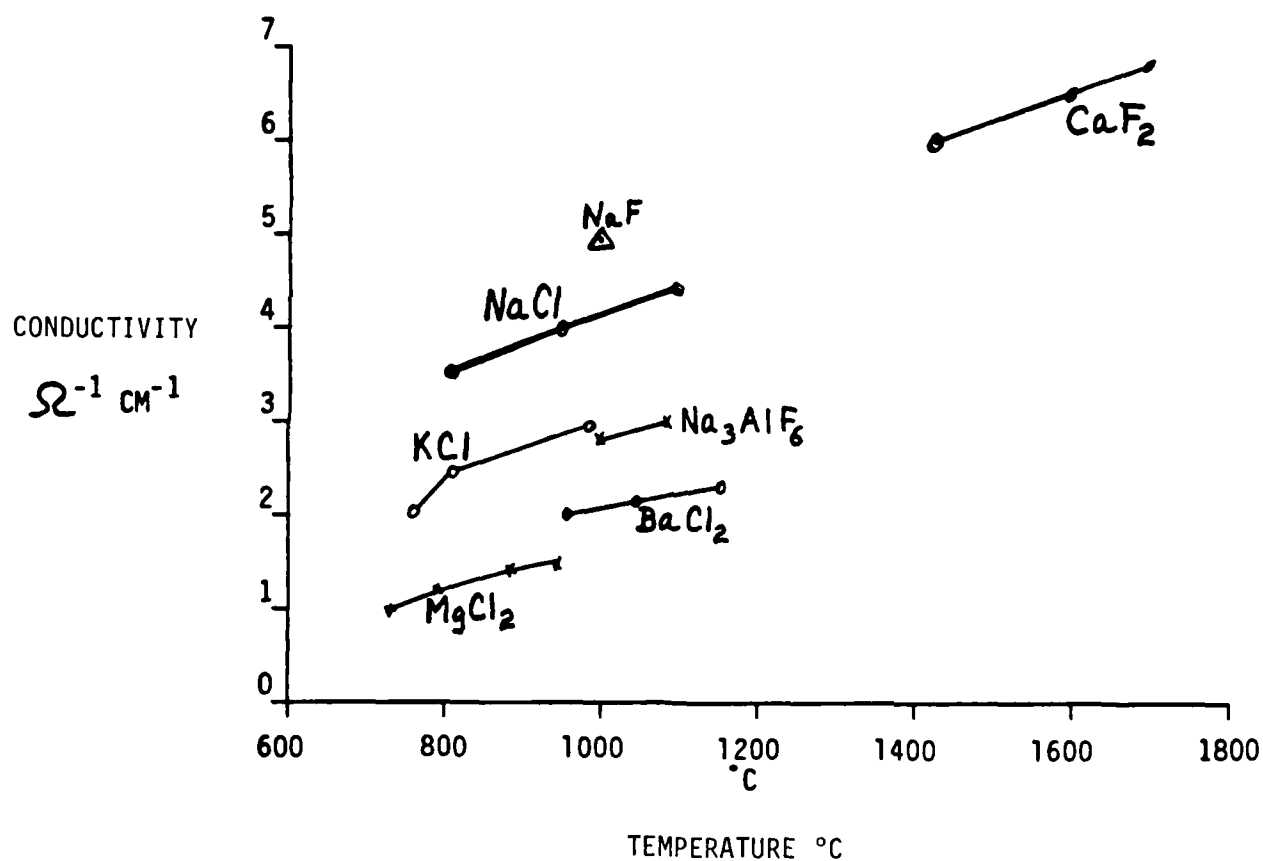


FIGURE 5.  
ESW TITANIUM  
FREE ENERGY OF FORMATION OF "GETTERS" AT 1500°K

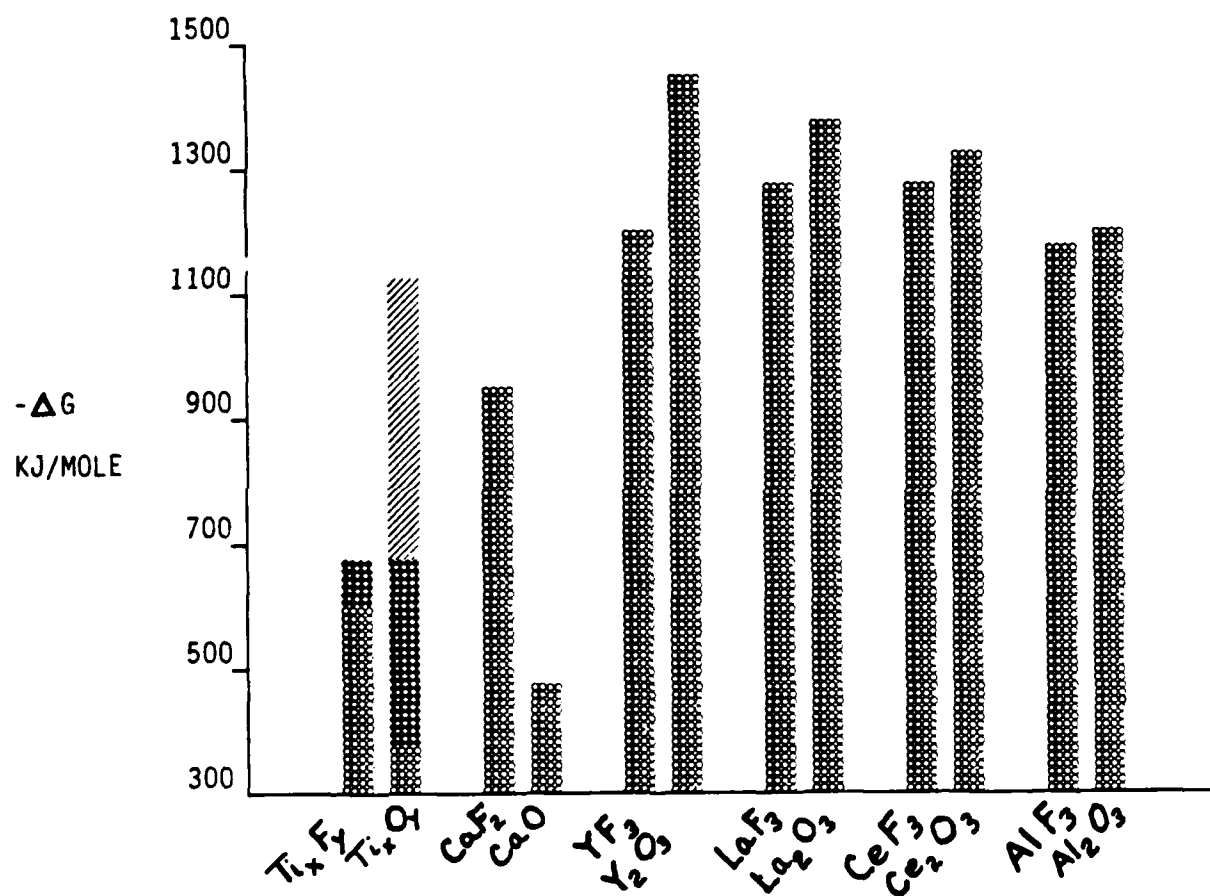
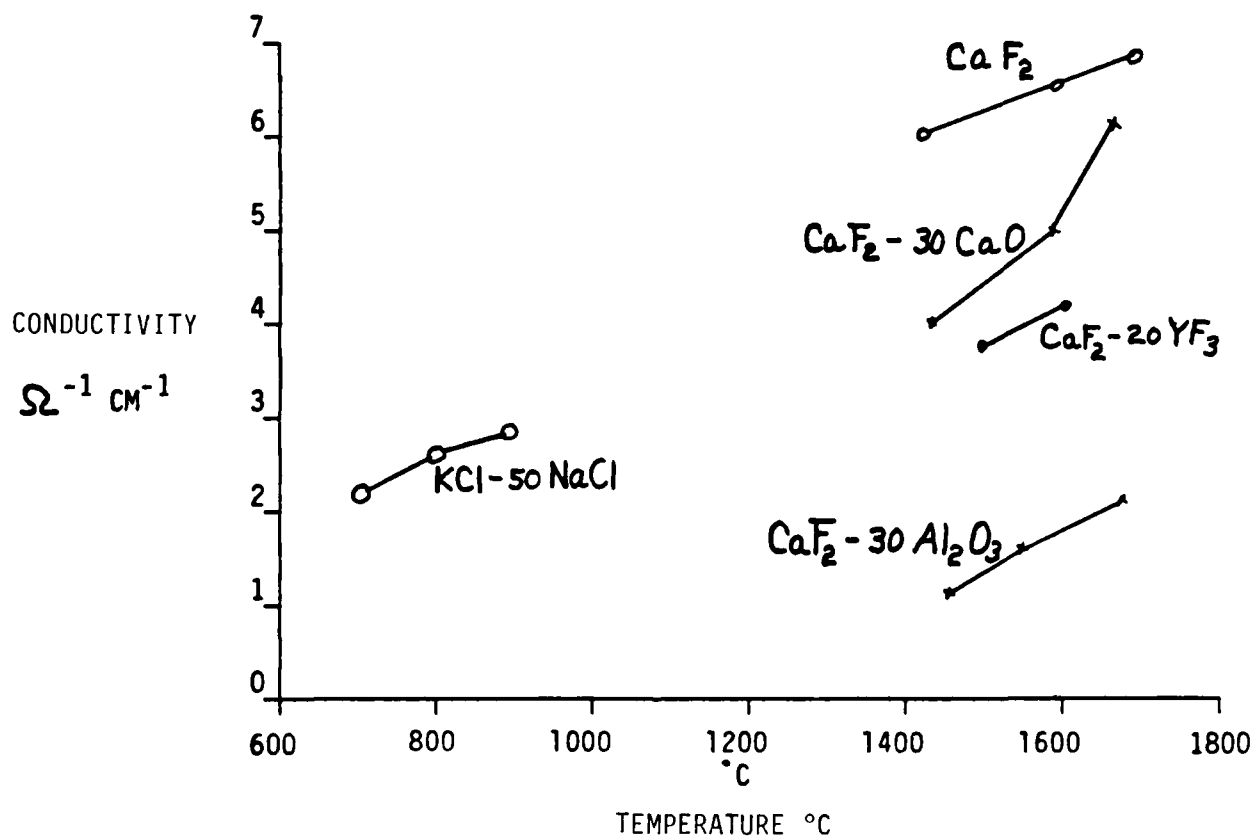
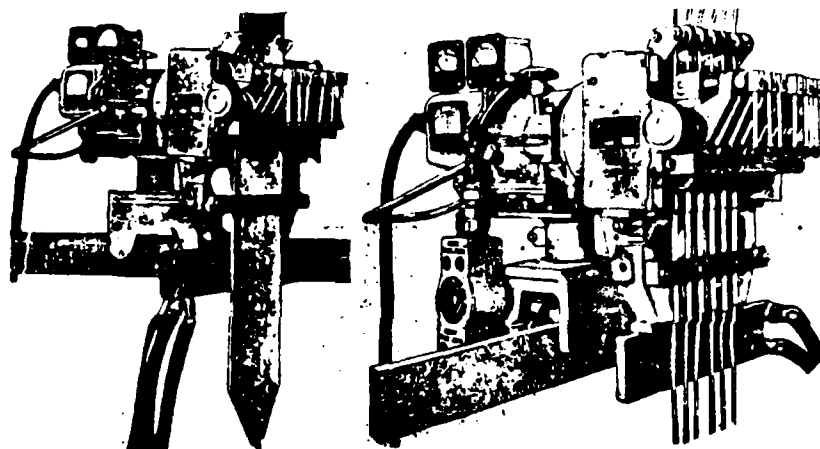


FIGURE 6.  
ELECTRICAL CONDUCTIVITY OF SLAGS





(A)

(B)

FIGURE 7. THE A-1126 APPARATUS, MODIFIED FOR  
(A) A PLATE ELECTRODE, AND  
(B) ELECTRODE WIRES.

Plate Thickness	2.0 inches	4.4 inches
Number of Electrodes	2	2
Electrode Feed Rate	117 ipm	117 ipm
Welding Current	1300 amp	1700 amp
Voltage	22 volts	22 volts
Depth of Slag Pool	1 inch	1 inch
Argon Flow	19 cfh	25 cfh
Distance Between Electrodes	1.6 inches	3.2 inches

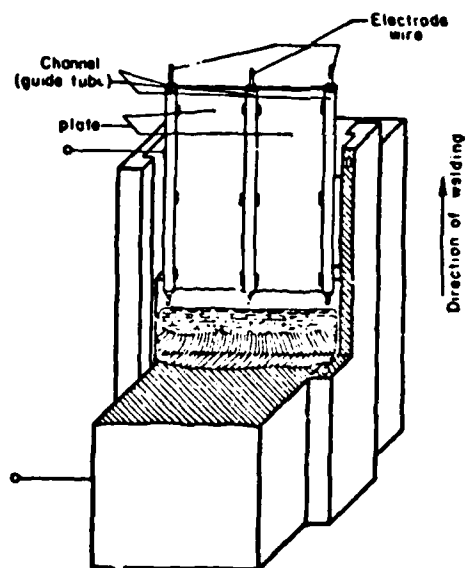


FIGURE 8. ELECTROSLAG WELDING WITH A CONSUMABLE NOZZLE.

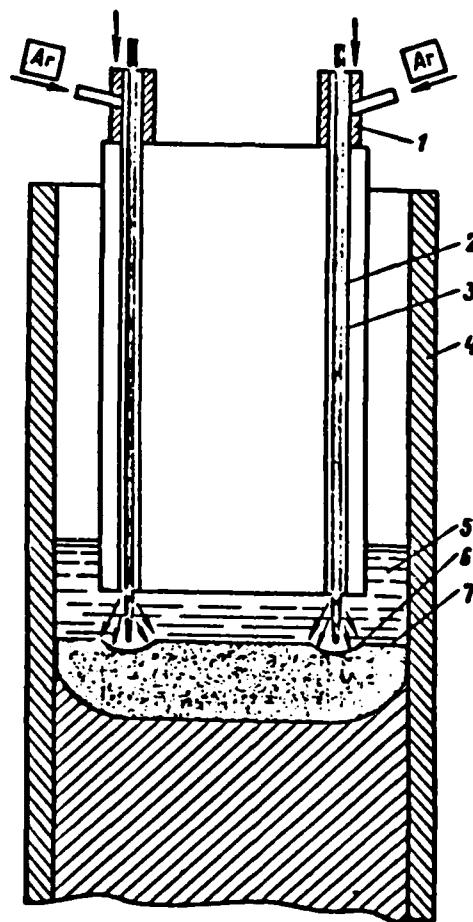


FIGURE 9. ESW WITH A CONSUMABLE GUIDE AND ARGON LANCING:

1—gas chamber; 2—electrode; 3—consumable tip; 4—forming plate; 5—slag pool; 6—metal pool; 7—weld

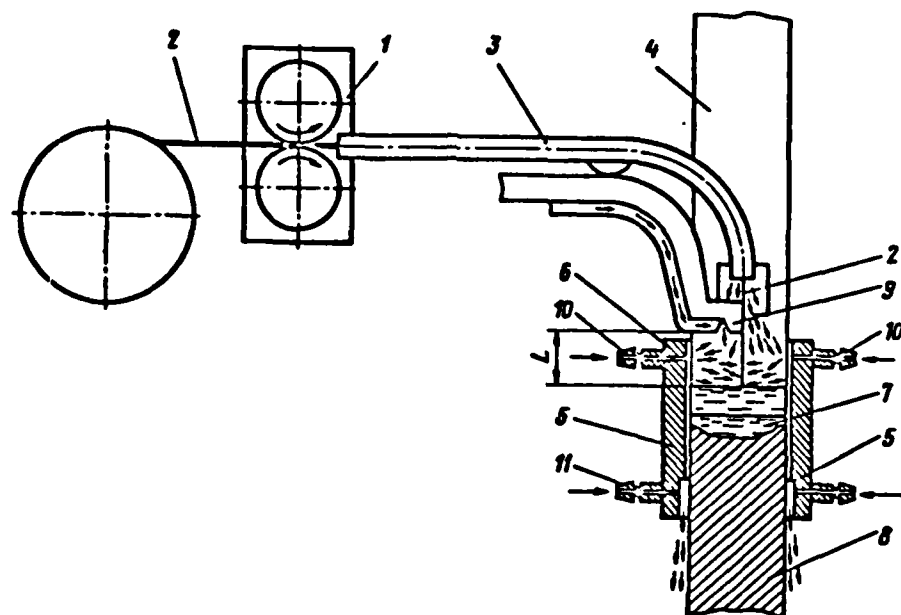


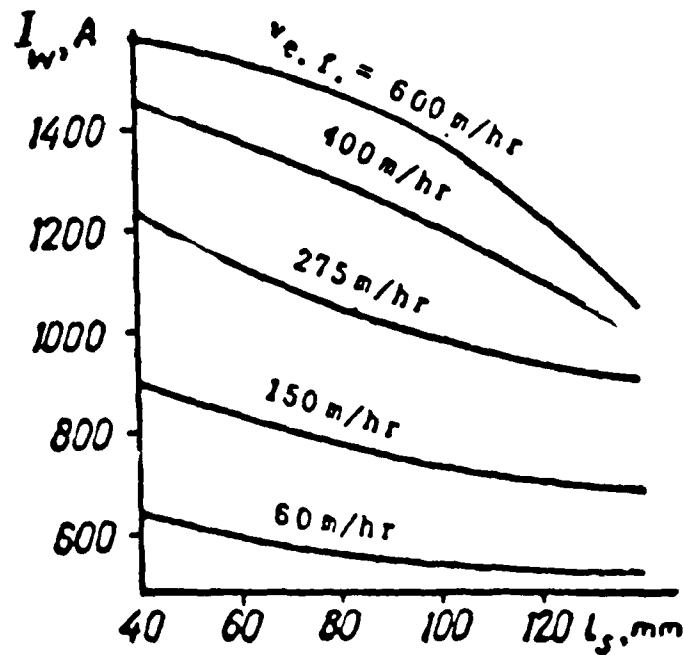
FIGURE 10.

A-1022 unit for ESW of titanium alloys:  
 1—feeding mechanism; 2—electrode; 3—welding tip; 4—article to be  
 welded; 5, 6—forming slide; 7—metal pool; 8—weld; 9—current-  
 supplying plug; 10, 11—coupling



FIGURE 11.

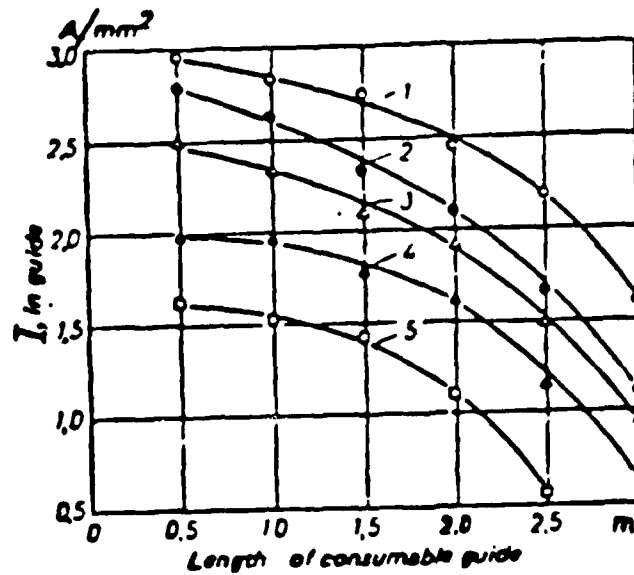
CONVENTIONAL ESW OF TITANIUM:



WELDING CURRENT VS. DRY ELECTRODE STICKOUT AT 30V

FIGURE 12.

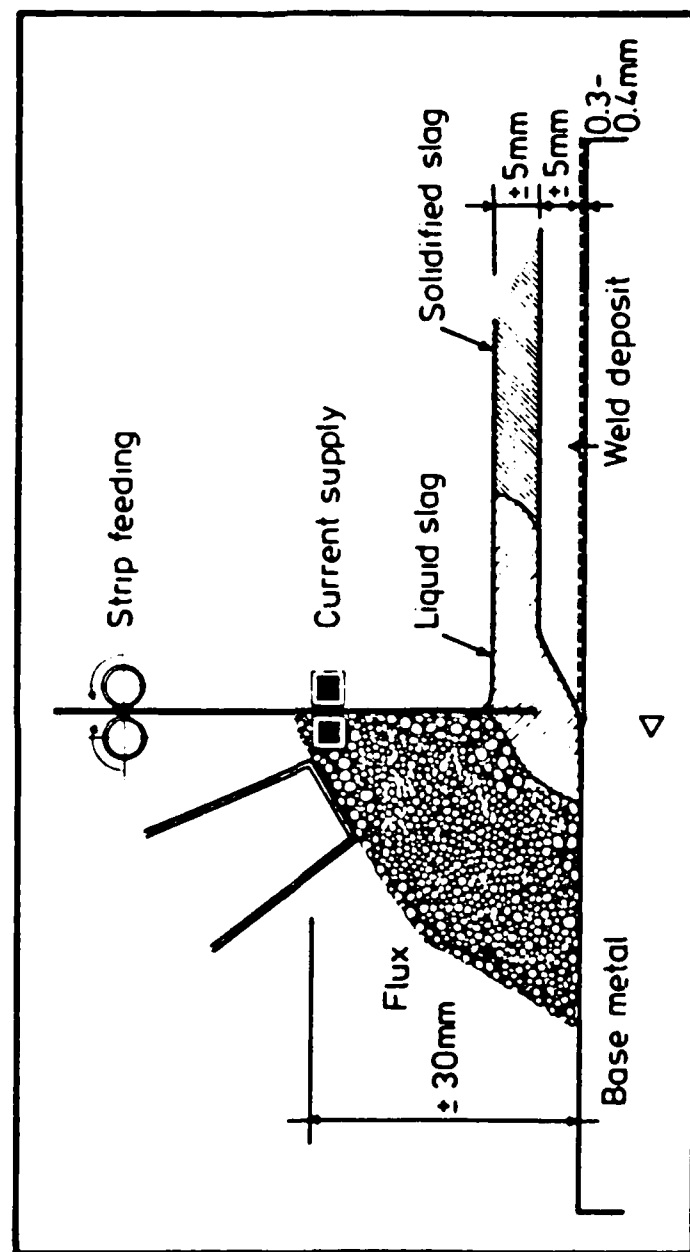
CONSUMABLE GUIDE ESW OF TITANIUM:



CURRENT DENSITY VS. ALLOWABLE LENGTH FOR (1) Ti, (2) Ti-3Al, (3) Ti-6Al-4V, (4) VT22, AND (5) VT22M ALLOY.

FIGURE 13.

## Electroslag cladding using nickel base alloys



1 Principle of electroslag strip cladding.

## EVALUATION OF ELECTROSLAG CASTINGS\*

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### ABSTRACT

Results of evaluations of electros slag castings of ferritic (2 1/4 Cr-1 Mo and 9 Cr-1 Mo) and austenitic (CF8M or type 316) steels are presented. The castings have been characterized for surface finish, cracking, solidification structure, chemical composition, hardness, ferrite distribution, tensile properties, Charpy impact properties, and creep properties. Pertinent data are compared with equivalent data for sand castings and wrought products of the same materials. Based on the results of these studies, the properties of electros lag castings compare favorably with those of sand castings and wrought materials.

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### INTRODUCTION

The Surface Gasification Materials Program electros lag casting (ESC) project is directed to the development of ESC technology for use in coal conversion components such as valves and pump housings. The purpose is to develop a sufficient data base to permit acceptance of ESC as an ASME Code material and to transfer the ESC process technology to private industry. The task emphasizes four major areas: (1) advancement of ESC technology, (2) preparation of castings (by commercial vendors), (3) testing [by Oak Ridge National Laboratory (ORNL)] of commercial ESCs for mechanical properties, and (4) participation with industrial component fabricators to demonstrate their ability to produce representative components for coal conversion systems by the ESC process.

Subcontractor support for this project is being provided by Cameron Iron Works, Selectrotech Products, Inc. (under subcontract to Mellon

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\*Research sponsored by the U.S. Department of Energy, Surface Gasification Materials Program (DOE/FE AA 85 45 10 0), under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

Institute of Research), and the University of Alabama in Birmingham. Cameron is producing several electroslag castings for evaluation at ORNL and is evaluating the capability of the electroslag casting process as a method of producing high integrity components. Selectrotech is developing and demonstrating several ESC manufacturing techniques, investigating methods for producing ESC molds at low costs, and making several electroslag castings for evaluation by ORNL. The University of Alabama in Birmingham is performing microstructural characterizations of CF8M (cast type 316 stainless steel) electroslag castings produced by Cameron and Selectrotech. In addition to these subcontractor R&D efforts, we have purchased several castings from the University of British Columbia. These castings are also being evaluated at ORNL.

At ORNL, mechanical properties evaluations of the castings are being made. The goal is to develop a sufficient data base to permit acceptance of ESC as an ASME Code material and to transfer the technology to private industry. Involvement of Cameron and Selectrotech in this work has helped achieve the goal of transferring this technology to industry as these organizations have made substantial investments in establishing ESC capabilities. In this paper some of our recent results of mechanical properties evaluations are presented.

#### ELECTROSLAG CASTINGS RECEIVED FROM SUBCONTRACTORS

Seven electroslag cast valve bodies were obtained from the University of British Columbia: four of type 316 stainless steel, two of 9 Cr-1 Mo, and one of 2 1/4 Cr-1 Mo steel. Figures 1 and 2 indicate the shapes and surface condition of the castings. Selectrotech Products, Inc. produced nine electroslag castings for evaluation. Selectrotech castings included two- and three-step blocks in 2 1/4 Cr-1 Mo, 9 Cr-1 Mo, and type 316 stainless steel. Typical Selectrotech castings are shown in Figs. 3-4. Cameron Iron Works produced eleven two-step block castings: four of 2 1/4 Cr-1 Mo, three of 9 Cr-1 Mo, and four of type 316 stainless steel; and three valve body castings: one each of 2 1/4 Cr-1 Mo, 9 Cr-1 Mo, and type 316 stainless steel. Typical castings from Cameron Iron Works are shown in Figs. 5-6.

Y-190722



Fig. 1. Electroslag cast valve bodies of 2 1/4 Cr-1 Mo and 9 Cr-1 Mo steels made at the University of British Columbia.

Y-194236



Fig 2. Front view of electroslag-cast valve bodies of CF8M steel made at the University of British Columbia.



Fig. 3. Three electroslag-cast step blocks of type 316 stainless steel received as part of the first batch of castings from Selectrotech. The casting tops are in front. The starter plates on the bottoms of the castings are visible in back.

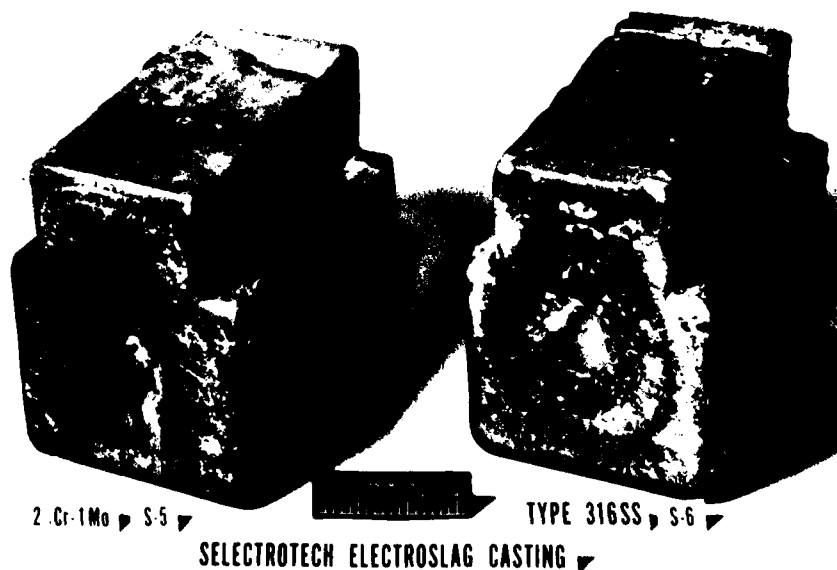


Fig. 4. The 2 1/4 Cr-1 Mo and type 316 stainless steel castings received as the second batch of castings from Selectrotech. Both were made with misch metal additions for grain refinement. The casting tops are in front.

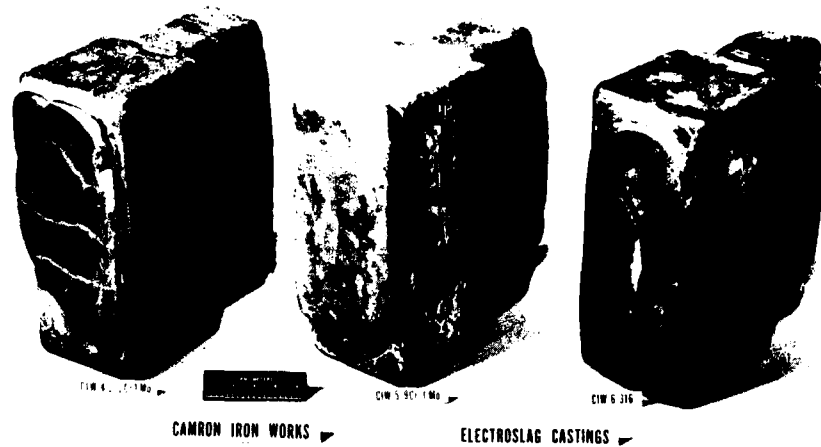


Fig. 5. Electroslag-cast step blocks received from Cameron Iron Works. They are, left to right, of 2 1/4 Cr-1 Mo, 9 Cr-1 Mo, and type 316 stainless steel. The casting tops are in front.

Y-P321

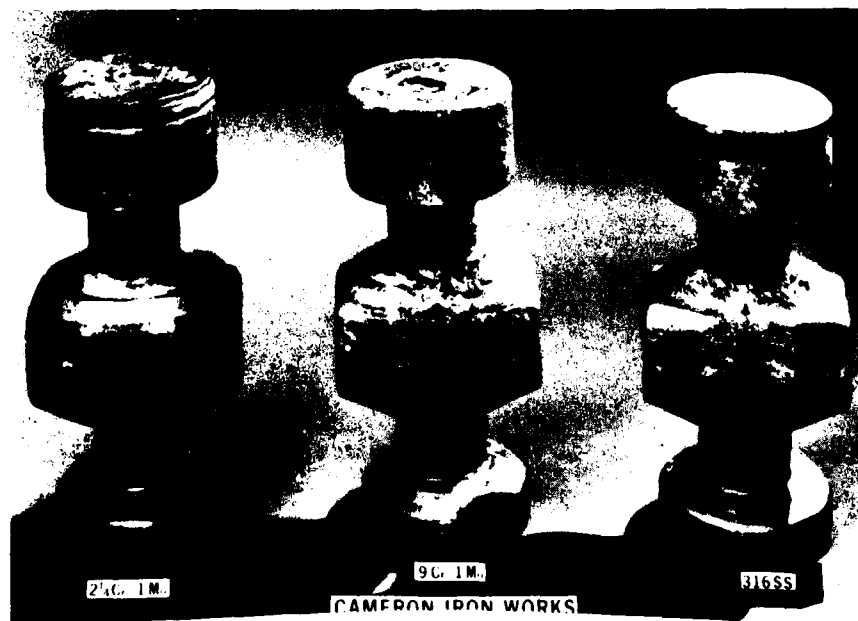


Fig. 6. Electroslag-cast valve bodies produced at Cameron Iron Works.

ORNL evaluated the castings from these three vendors for quality, response to heat treatment, and mechanical properties. Mechanical properties tested include Charpy impact, tensile strength, and creep strength. Properties of the electroslag castings were compared to determine the differences between casters, between wrought and electroslag cast properties, and between sand and electroslag castings. The remainder of this paper will focus on the ORNL evaluation of the electroslag castings and, although castings of specific materials from specific vendors will be discussed, the results presented are typical of all castings evaluated.

#### HEAT TREATMENT, MACROSTRUCTURE, AND CHEMICAL ANALYSIS

The ferritic steels (2 1/4 Cr-1 Mo and 9 Cr-1 Mo) were normalized (1040°C) and tempered (760°C) before testing. The as-cast structures of all the electroslag castings were very coarse [see Fig 7(a)]. As may be observed in Fig. 7(b), normalizing and tempering of the ferritic steels produces a very fine macrostructure.

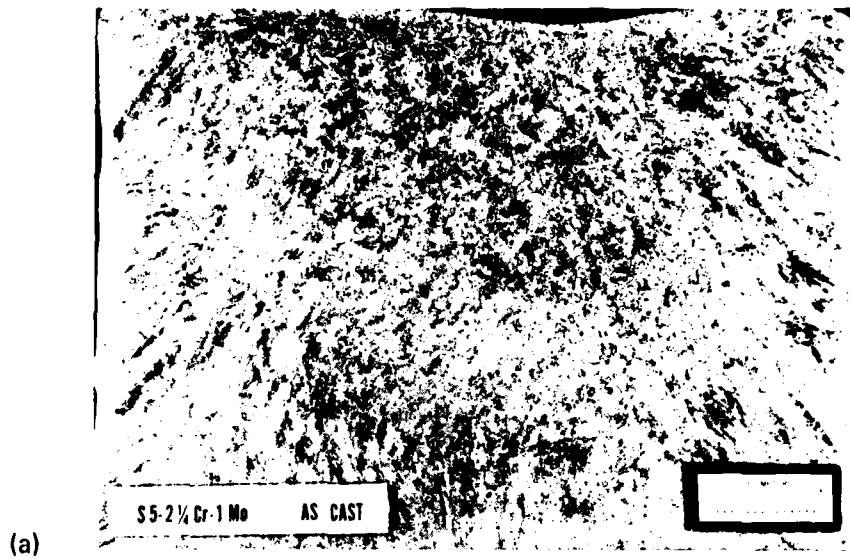
Results of chemical analyses of the starting electrode and of the top and bottom of the resulting two-step electroslag casting of 9 Cr-1 Mo steel (CIW-5) from Cameron Iron Works are given in Table 1. All elements transferred satisfactorily from the electrode to the casting. The silicon content was lowered somewhat and the aluminum content increased. The silicon was probably oxidized to  $\text{SiO}_2$  and extracted into the basic slag. The aluminum content increased in the casting because of its addition during casting to effect deoxidation. The relative amounts of these elements can be adjusted by controlling the casting parameters.

The austenitic stainless steel (type 316 or CF8M) castings were solution annealed (1065°C for 1 h per 25 mm of thickness) prior to testing. Macrostructures of electroslag-cast type 316 stainless steel are essentially unchanged by this heat treatment.

Chemical analysis data for a CF8M electroslag casting produced at the University of British Columbia are presented in Table 2. These data show that all elements are distributed uniformly from top-to-bottom in the casting.



Y-197148



Y-197118

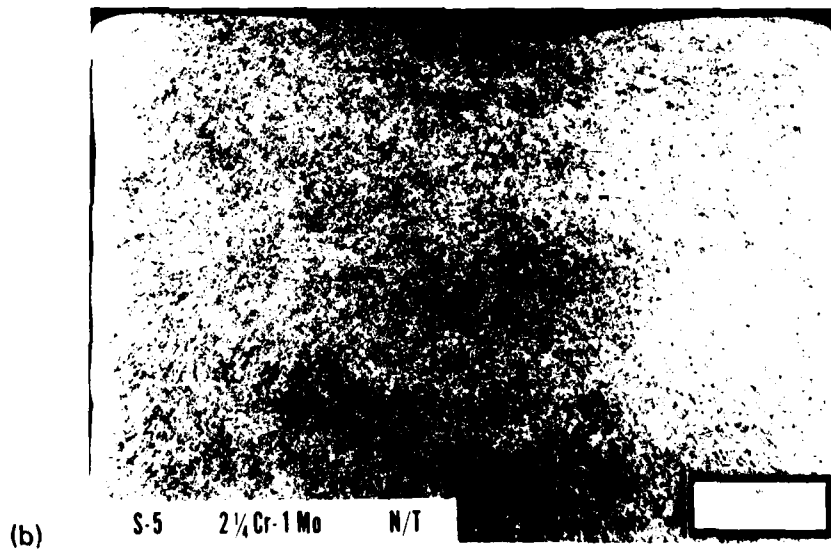


Fig. 7. Macrostructure comparison of as-cast and normalized-and-tempered conditions of a two-step electrosag-cast block of 2 1/4 Cr-1 Mo steel with misch metal addition (S-5) from Selectrotech.

Table 1. Chemical analyses of starting electrode and of the resulting two-step electroslag casting of 9 Cr-1 Mo steel (CIW-5) from Cameron Iron Works

Element	Content (wt %)				
	Electrode	Casting			
		Top step		Bottom step	
		Top	Bottom	Top	Bottom
Carbon	0.089	0.091	0.088	0.087	0.095
Manganese	0.47	0.51	0.51	0.50	0.50
Phosphorus	0.021	0.018	0.018	0.019	0.020
Sulfur	0.006	0.001	0.001	0.001	0.001
Silicon	0.28	0.19	0.26	0.17	0.18
Nickel	0.16	0.15	0.15	0.16	0.15
Chromium	9.24	9.33	9.31	9.36	9.27
Molybdenum	0.96	1.01	1.00	1.01	1.01
Vanadium	0.21	0.20	0.20	0.20	0.20
Niobium	0.054	0.051	0.052	0.050	0.047
Titanium	0.002	0.001	0.002	0.001	0.002
Cobalt	0.019	0.022	0.022	0.022	0.022
Copper	0.08	0.08	0.08	0.08	0.08
Aluminum	0.002	0.044	0.052	0.041	0.087
Boron	<0.001	<0.001	<0.001	<0.001	<0.001
Tungsten	0.01	0.01	0.01	0.01	0.01
Arsenic	0.002	0.005	0.004	0.005	0.004
Tin	0.004	0.004	0.004	0.004	0.004
Zirconium	<0.001	<0.001	<0.001	<0.001	<0.001
Nitrogen	0.035	0.036	0.037	0.037	0.036
Oxygen	0.008	0.003	0.003	0.003	0.003

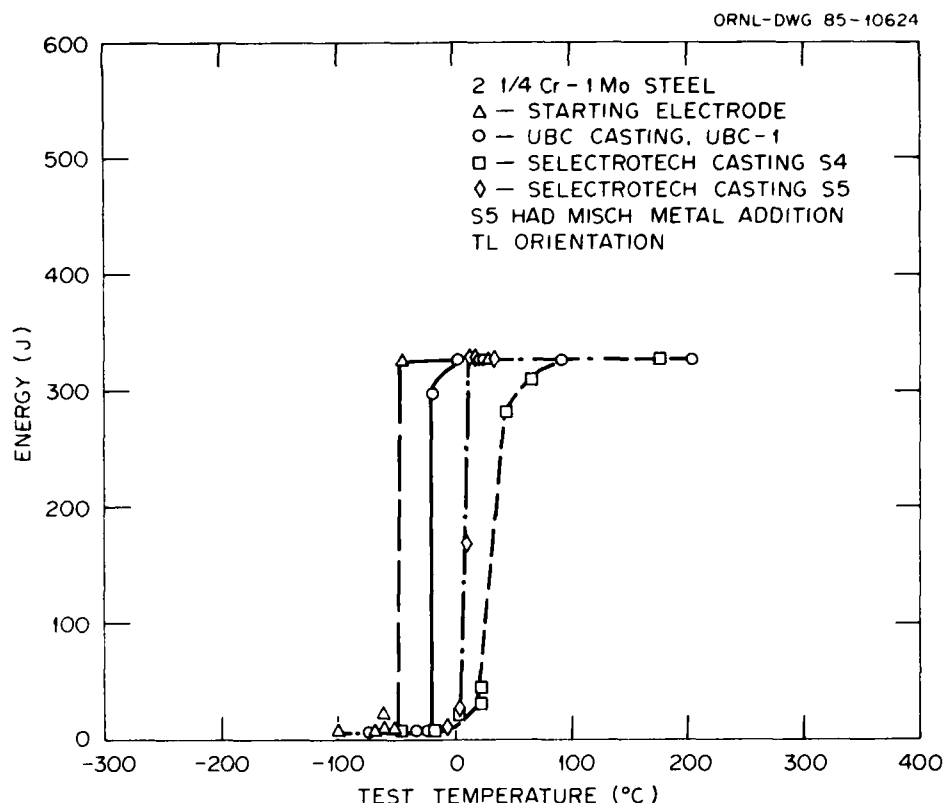


Fig. 8. Charpy impact energy curves for TL-orientation specimens of the starting electrode, electroslog-cast valve body from the University of British Columbia, Vancouver, Canada, and two-step blocks from Selectrotech of 2 1/4 Cr-1 Mo steel with and without misch metal addition (S-5 and S-4) All materials were tested in the normalized-and-tempered condition. Energy values of 326 J on this plot represent the stopped hammer condition.

## MECHANICAL PROPERTIES

### Charpy Impact Properties

Charpy impact energy plots for electroslog-cast step blocks of 2 1/4 Cr-1 Mo steel with (casting S-5) and without (casting S-4) misch metal additions for TL- and LT-orientation specimens are shown in Figs. 8 and 9, respectively. Both castings were made at Selectrotech and were tested in the normalized and tempered condition. As may be noted from these figures, the impact energy curves for the electroslog casting are shifted by 50°C to the right as compared with the wrought material. Thus, the transition temperature for the casting will be 50°C higher than the

Table 2. Chemical analyses conducted at Combustion Engineering, Chattanooga, Tenn.,  
on electroslag cast valve body 3 of CF8M

Element	Content (wt %) in each specimen <sup>a</sup>										Starting electrode
	1	2	3	4	5	6	7	8	9	10	
Carbon	0.065	0.075	0.079	0.074	0.076	0.079	0.073	0.076	0.073	0.073	0.070
Manganese	0.71	0.69	0.71	0.71	0.70	0.71	0.69	0.69	0.70	0.71	0.72
Phosphorus	0.040	0.037	0.038	0.038	0.037	0.038	0.034	0.035	0.036	0.037	0.037
Sulfur	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.006
Silicon	1.22	1.15	1.19	1.20	1.18	1.20	1.17	1.22	1.18	1.19	1.26
Nickel	9.28	9.04	9.24	9.20	9.19	9.23	9.01	9.16	9.19	9.18	9.05
Chromium	18.46	18.28	18.50	18.49	18.57	18.54	18.54	18.54	18.54	18.46	18.45
Molybdenum	2.24	2.19	2.23	2.22	2.22	2.23	2.19	2.21	2.23	2.23	2.23
Vanadium	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.06
Niobium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Titanium	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cobalt	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Copper	0.14	0.13	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.14	0.14
Aluminum	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Boron	<0.001	<0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	<0.001
Nitrogen	0.068	0.061	0.063	0.066	0.059	0.063	0.055	0.059	0.059	0.057	0.064
Oxygen	0.0071					0.0028				0.0024	

<sup>a</sup>Specimens taken about 25 mm apart from top (specimen 1) to bottom (specimen 10) in the 1/2-thickness section of the casting.

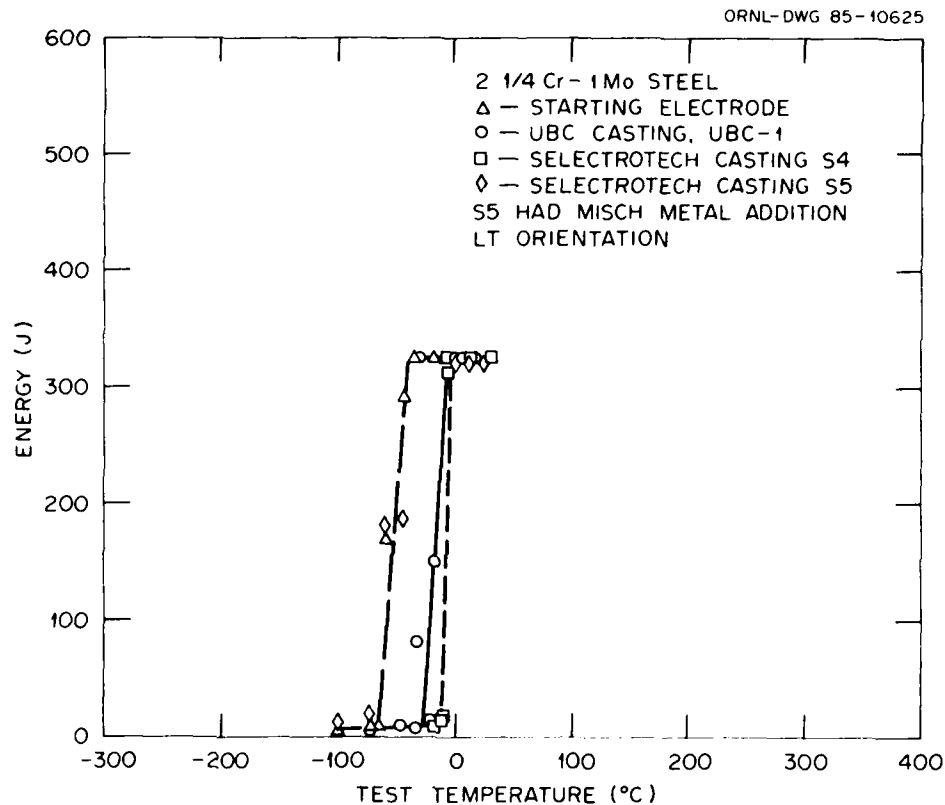


Fig. 9. Charpy impact energy curves for LT-orientation specimens of the starting electrode, electroslag-cast valve body from the University of British Columbia, Vancouver, Canada, and two-step blocks from Selectrotech of 2 1/4 Cr-1 Mo steel with and without misch metal addition (S-5 and S-4). All materials were tested in the normalized-and-tempered condition. Energy values of 326 J on this plot represent the stopped-hammer condition.

wrought product. However, the transition temperatures for the electroslag-cast ferritic steels are typically about 50°C lower than for sand castings of the same material.

Room-temperature Charpy impact properties of electroslag castings of type 316 stainless steel are generally about the same for all the castings. Typically, these impact energies exceed the machine capacity (326 J).

### Tensile Properties

The tensile strength and ductility properties of an electroslag-cast valve body from the University of British Columbia and a two-step block electroslag casting from Cameron Iron Works of 2 1/4 Cr-1 Mo steel are plotted in Fig. 10-13. Properties of the plate used as the electrode material are also included for comparison. Yield and ultimate tensile strength values of the 2 1/4 Cr-1 Mo steel electroslag castings approach or exceed the average curve for the wrought material. The behavior of the tensile properties of 9 Cr-1 Mo steel (also a ferritic steel) is similar to that of the 2 1/4 Cr-1 Mo steel.

Tensile properties of two electroslag-cast step blocks from Cameron Iron Works and three electroslag-cast valve bodies of type 316 stainless steel from the University of British Columbia are compared with those of sand castings in Figs. 14-18.

Tensile properties of the type 316 stainless steel electroslag castings are similar to those of sand castings. The solid-state transformational products (bainite or martensite) from austenite are responsible for the improvements in strength properties in the ferritic steels. These transformations do not, of course, occur in the austenitic stainless steels.

### Creep Testing

Creep tests of 100-, 1000-, and 5000-h duration each are being run on longitudinal specimens (parallel to the solidification direction) and transverse specimens (perpendicular to the solidification direction) of each electroslag casting. Significant creep testing has been completed on three electroslag-cast valve bodies of type 316 stainless steel from the University of British Columbia. A parametric plot of the stress-rupture data for these castings is presented in Fig. 19. The rupture behavior of the three valve body castings is nearly the same. Rupture strength matches the minimum curve for wrought material, which matches the average curve for sand castings. The implication is that the creep-rupture strength of type 316 stainless steel electroslag castings is similar to that of sand castings.

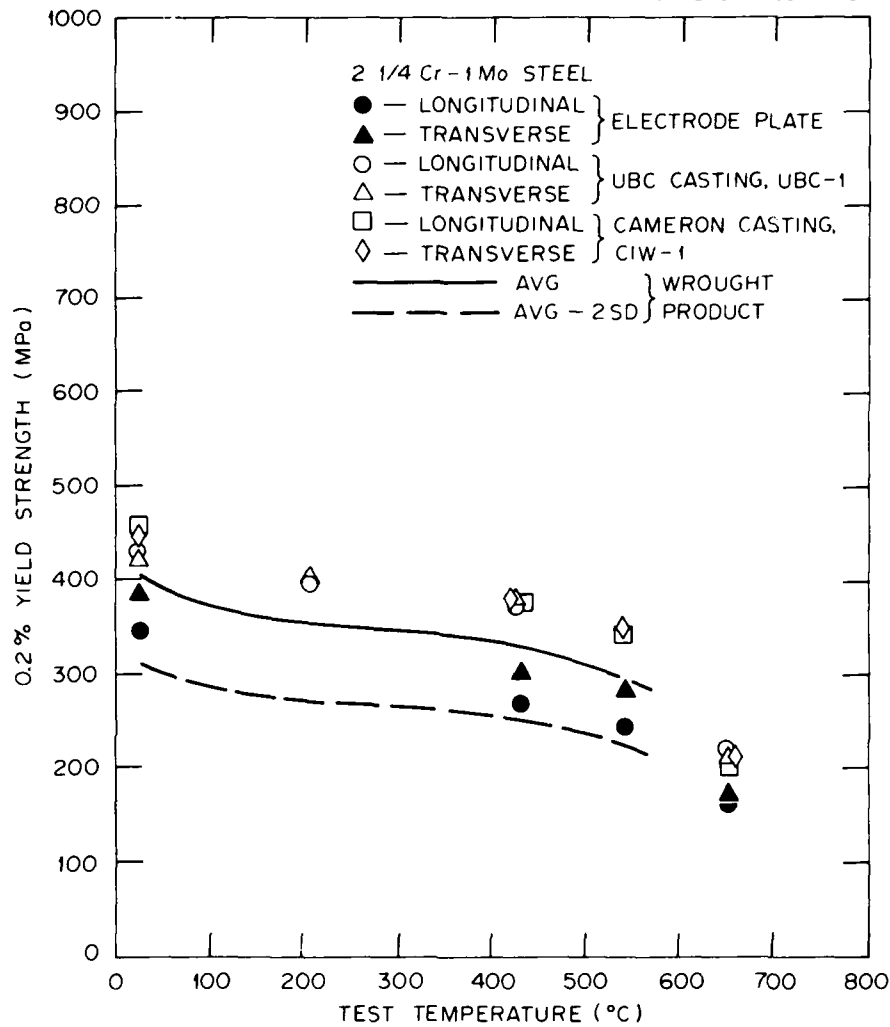


Fig. 10. Yield-strength plots for an electroslog-cast valve body from the University of British Columbia, Vancouver, Canada, a two-step casting from Cameron Iron Works, and the electrode material of 2 1/4 Cr-1 Mo steel. All materials were tested in the normalized-and-tempered condition. The average and average minus two times the standard deviation curves for wrought 2 1/4 Cr-1 Mo steel are included for comparison.

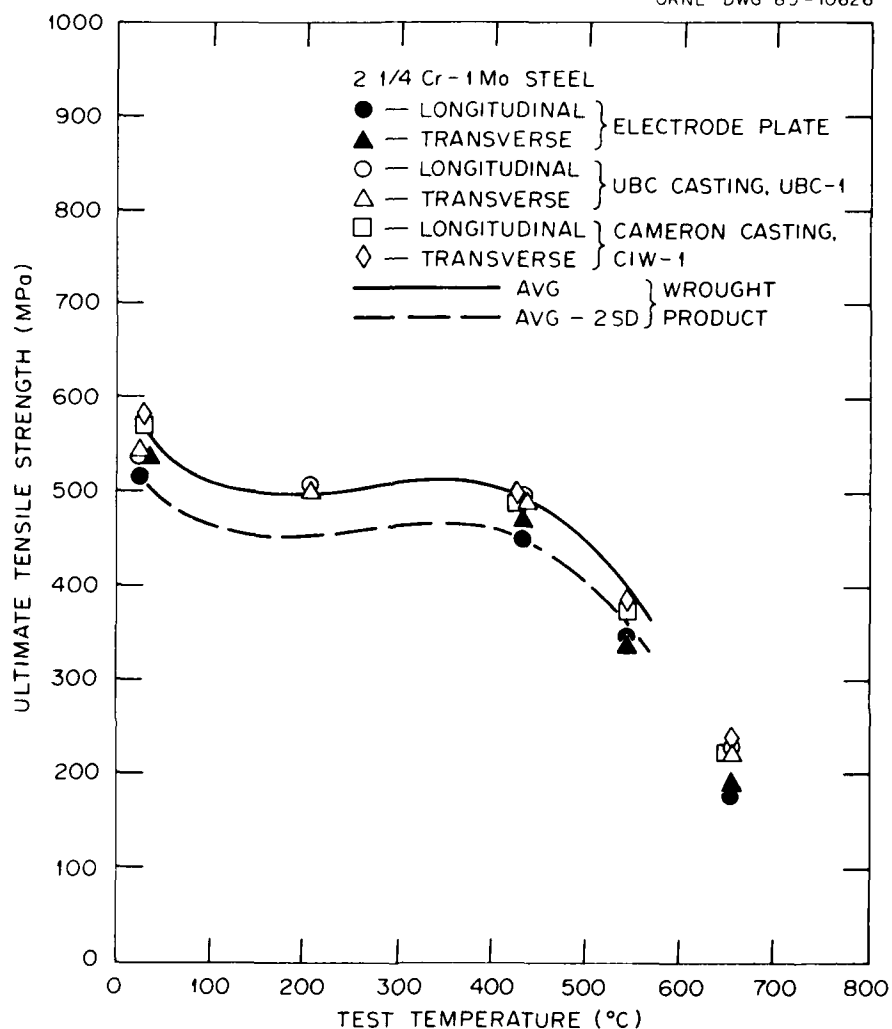


Fig. 11. Ultimate-tensile-strength plots for an electrosag-cast valve body from the University of British Columbia, Vancouver, Canada, a two-step casting from Cameron Iron Works, and the electrode material of 2 1/4 Cr-1 Mo steel. All materials were tested in the normalized-and-tempered condition. The average and average minus two times the standard deviation curves for wrought 2 1/4 Cr-1 Mo steel are included for comparison.



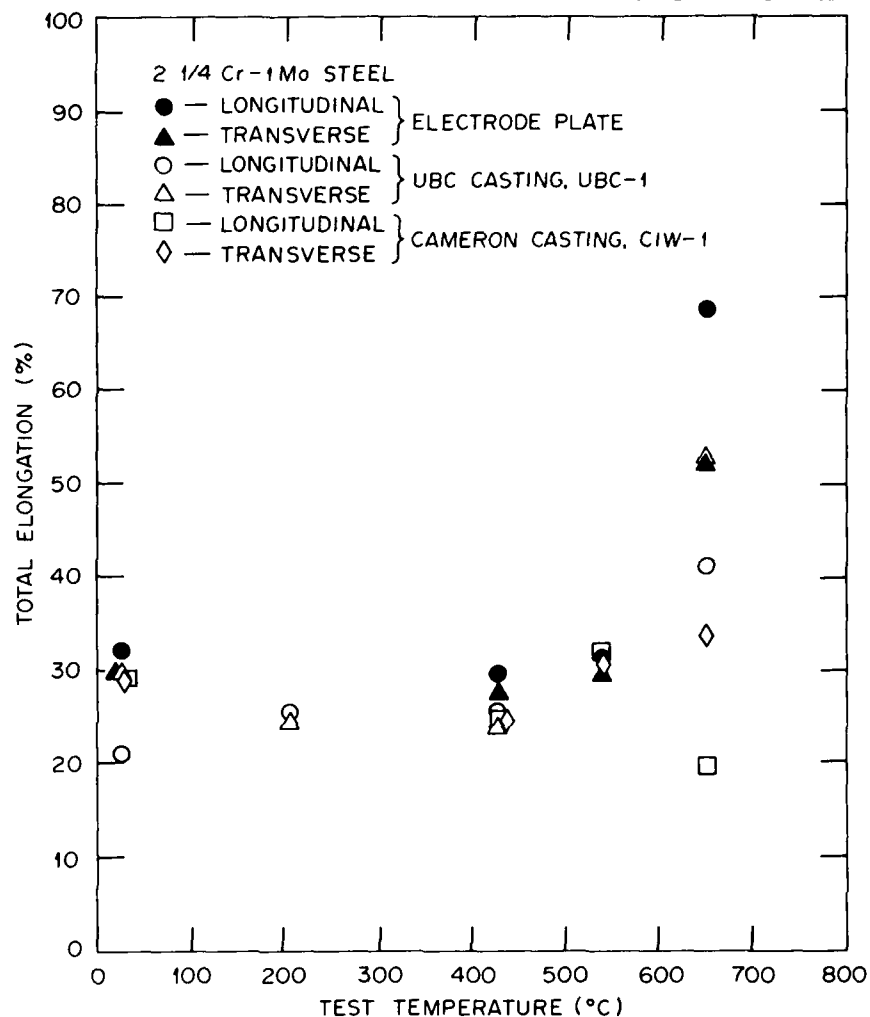


Fig. 12. Total-elongation plots for an electroslog-cast valve body from the University of British Columbia, Vancouver, Canada, a two-step casting from Cameron Iron Works, and the electrode material of 2 1/4 Cr-1 Mo steel. All materials were tested in the normalized-and-tempered condition.

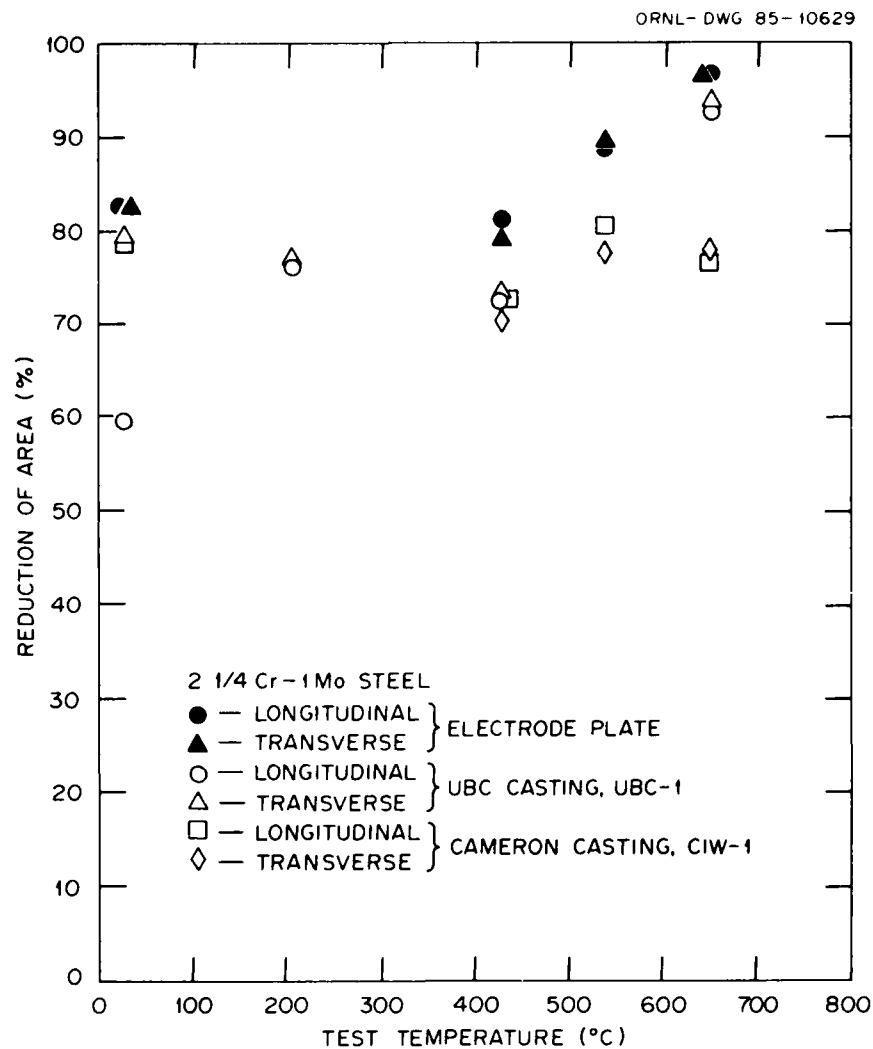


Fig. 13. Reduction-of-area plots for an electroslag-cast valve body from the University of British Columbia, Vancouver, Canada, a two-step casting from Cameron Iron Works, and the electrode material of 2 1/4 Cr-1 Mo steel. All materials were tested in the normalized-and tempered condition.

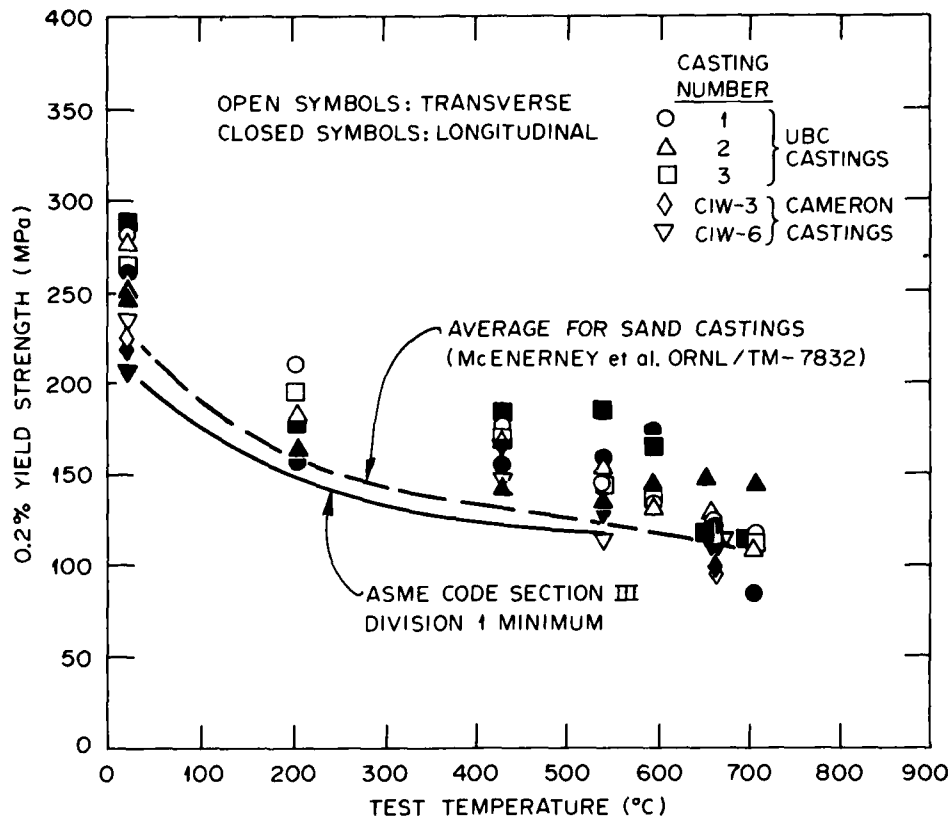


Fig. 14. The 0.2% yield strength as a function of test temperature for three electroslog-cast valve bodies of type 316 stainless steel from the University of British Columbia, Vancouver, Canada, and for two-step blocks from Cameron Iron Works. The average curve for sand castings from McEnerney, Sikka, and Booker and the ASME Code Section III, Div. 1, minimum for CF8M are also included.

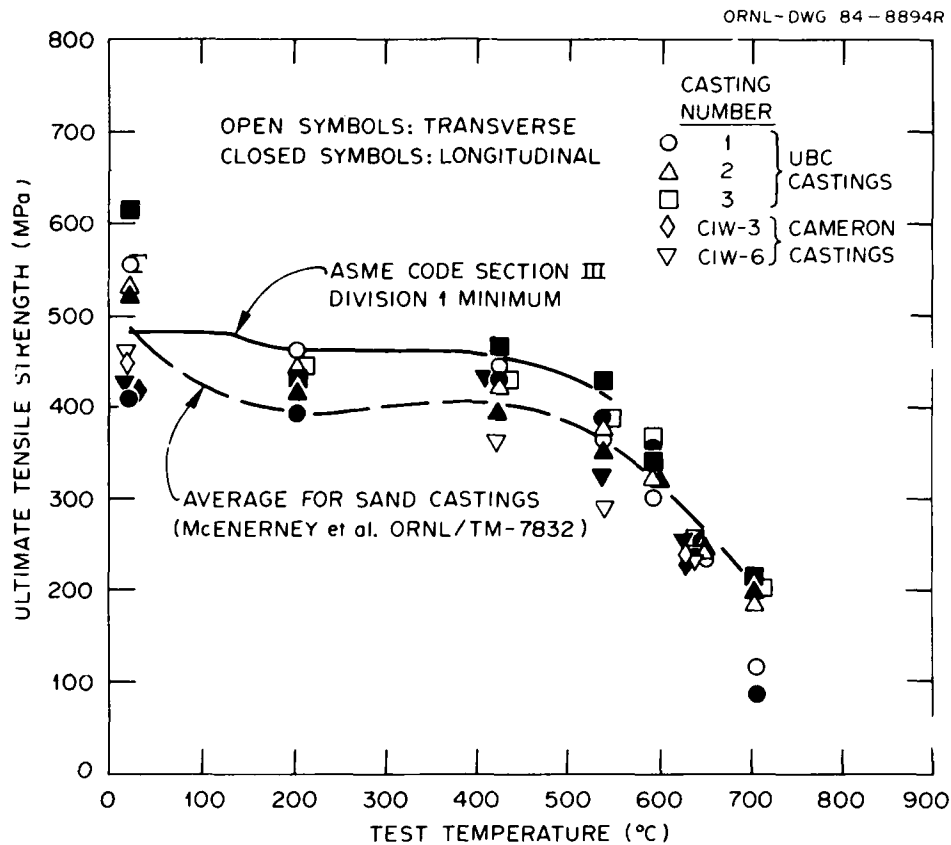


Fig. 15. Ultimate tensile strength as a function of test temperature for three electroslag-cast valve bodies of type 316 stainless steel from the University of British Columbia, Vancouver, Canada, and for two-step blocks from Cameron Iron Works. The average curve for sand castings from McEnerney, Sikka, and Booker and the ASME Code Section III, Div. 1, minimum for CF8M are also included.

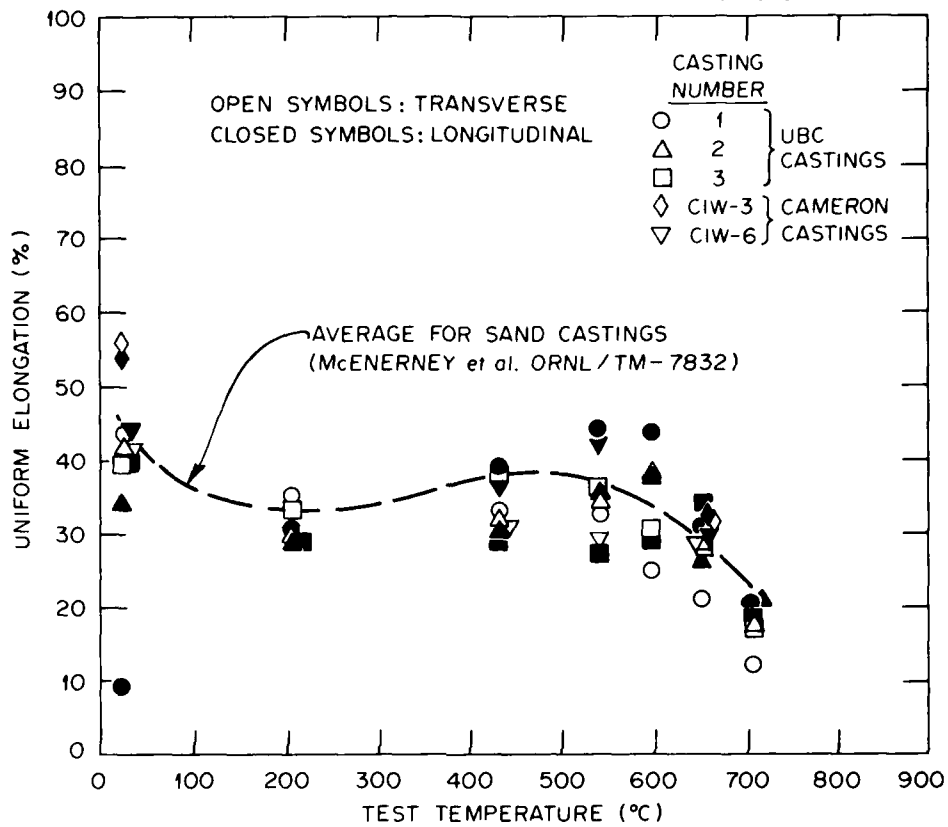


Fig. 16. Uniform elongation as a function of test temperature for three electroslag-cast valve bodies of type 316 stainless steel from the University of British Columbia, Vancouver, Canada, and for two-step blocks from Cameron Iron Works. The average curve for sand castings from McEnerney, Sikka, and Booker is also included.

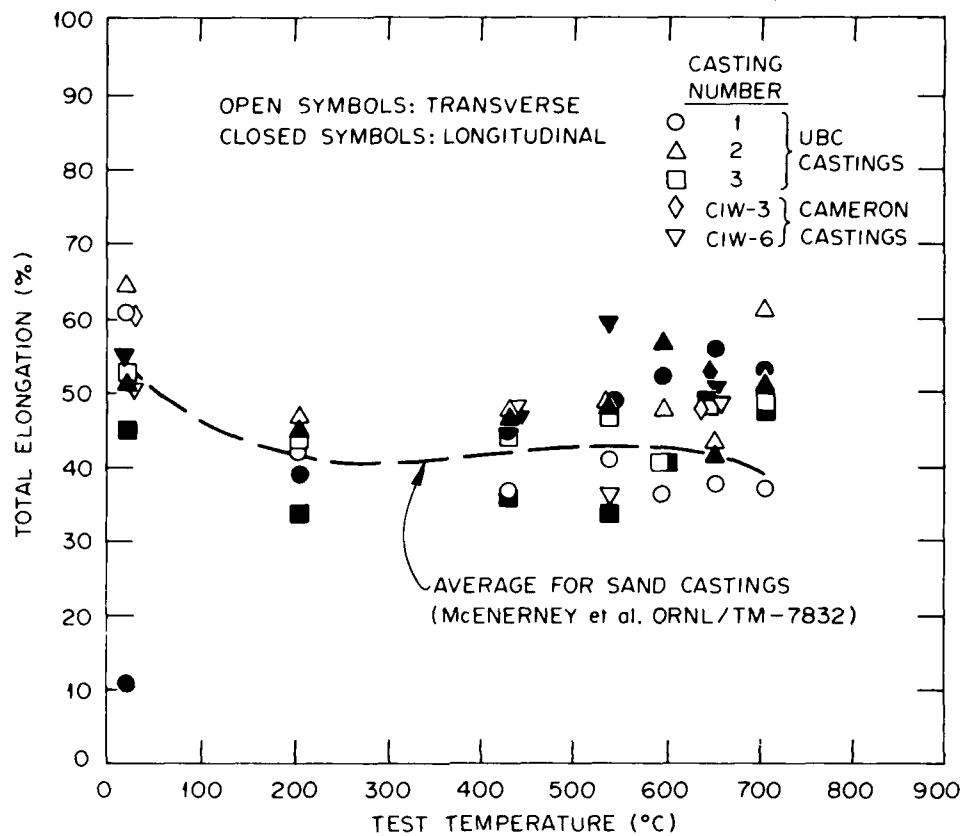


Fig. 17. Total elongation as a function of test temperature for three electroslog-cast valve bodies of type 16 stainless steel from the University of British Columbia, Vancouver, Canada, and for two-step blocks from Cameron Iron Works. The average curve for sand castings from McEnerney, Sikka, and Booker is also included.

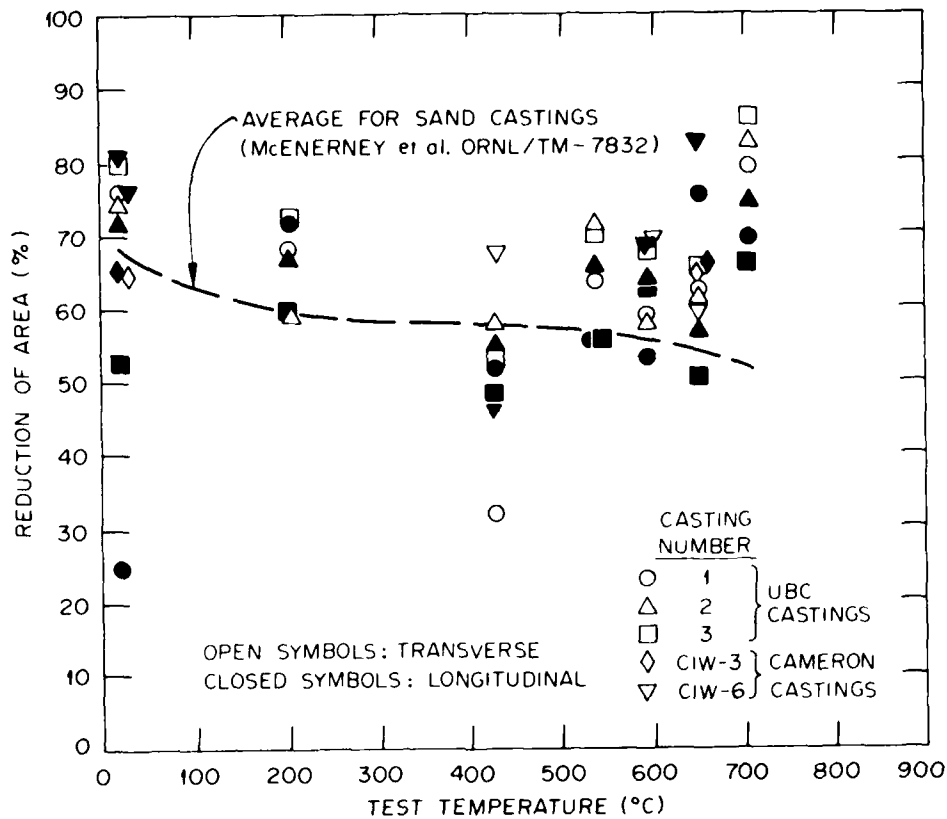


Fig. 18. Reduction of area as a function of test temperature for three electroslag-cast valve bodies of type 316 stainless steel from the University of British Columbia, Vancouver, Canada, and for two-step blocks from Cameron Iron Works. The average curve for sand castings from McEnerney, Sikka, and Booker is also included.

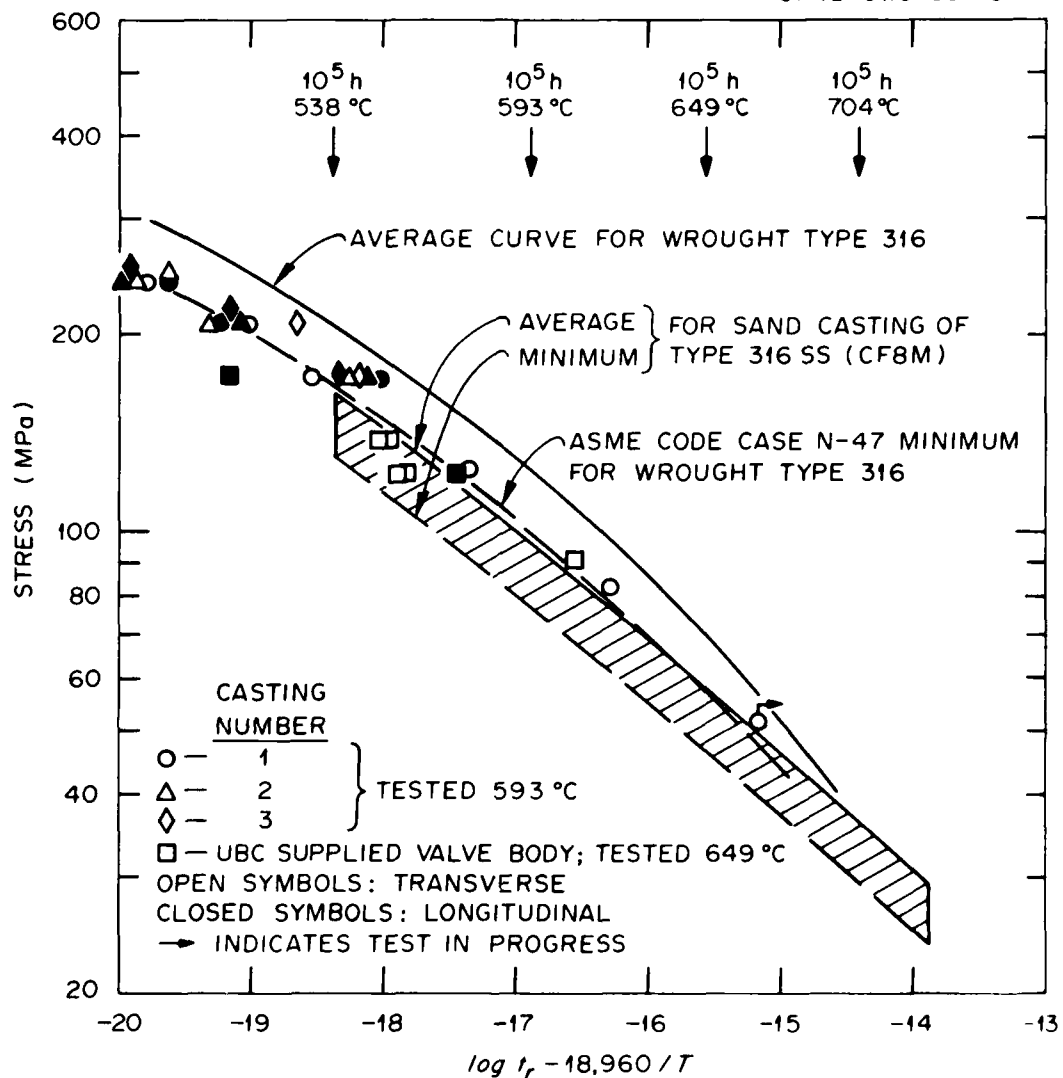


Fig. 19. Parametric stress-rupture plot for electroslog castings of type 316 stainless steel. Trends for wrought alloy and sand castings are included for comparison. The stress-rupture values for electroslog castings are closer to the average curve for sand castings.



## CONCLUSIONS

In this summary paper, we have presented results of our evaluation of electroslog-cast ferritic (2 1/4 Cr-1 Mo and 9 Cr-1 Mo) and austenitic (type 316 stainless) steels. The following conclusions are possible from this work.

1. Surface and internal quality of electroslog castings is generally very good. Filling of molds was a problem with the initial castings (see Fig. 5) at Selectrotech and Cameron Iron Works, but this problem was essentially eliminated as experience was gained.

2. For 2 1/4 Cr-1 Mo and 9 Cr-1 Mo steel castings, normalizing and tempering refined the as-solidified grain structure. Solution annealing the stainless steel castings produced no grain refinement. We believe that the solid-state transformation (austenite to bainite or martensite) that occurs in 2 1/4 Cr-1 Mo and 9 Cr-1 Mo steels is responsible for their grain refinement. Such transformations do not occur in austenitic stainless steels.

3. A complete transfer of constituents was observed from the electrodes to the electroslog castings.

4. The Charpy impact energy curves for electroslog castings of 2 1/4 Cr-1 Mo steel were shifted to the right by 50°C as compared with the wrought material. This means that the transition temperature of the electroslog castings will be 50°C higher than that of the wrought material. The misch metal addition shifted the impact-energy curve of the casting to the left. The shift was sufficient to warrant additional work to determine the amount to be added and its effect.

5. The transition from the ductile to brittle region was very abrupt in both wrought and electroslog-cast 2 1/4 Cr-1 Mo steel. This feature of the curve will necessitate the use of temperature for the start of upper-shelf energy as the design criterion rather than the conventional 68-J temperature.

6. The ductile-to-brittle transition for 9 Cr-1 Mo steel was more gradual than that for 2 1/4 Cr-1 Mo steel.

7. The Charpy impact energy for the University of British Columbia 9 Cr-1 Mo steel casting matched that of the wrought electrode material, which implies that electroslog casting has the potential of producing impact values approaching those of the wrought material. As compared with the wrought material, the impact energy curves for the Cameron Iron Works castings were shifted to the right by 40 to 70°C. We believe that this shift will be minimized as process parameters are optimized.

8. All Charpy impact specimens of type 316 stainless steel castings from Cameron Iron Works stopped the hammer at room temperature, which means that the castings had an impact energy greater than 326 J.

9. Yield and ultimate tensile strength values of 2 1/4 Cr-1 Mo electroslog castings approached or exceeded the average curve for the wrought material. Total-elongation and reduction-of-area values were similar to those observed for the wrought material.

10. Tensile properties of 9 Cr-1 Mo steel castings approached the average properties of the wrought material. This behavior is similar to that observed for 2 1/4 Cr-1 Mo steel.

11. Tensile properties of type 316 stainless steel castings are similar to those of sand castings. The solid-state transformational products from austenite are responsible for improvements of strength properties in 2 1/4 Cr-1 Mo and 9 Cr-1 Mo steels. Similar transformations do not occur in austenitic stainless steels. Thus, improvements in properties of electroslog-cast austenitic stainless steels can probably not be accomplished by heat treatment.

12. The creep-rupture strength of type 316 stainless steel electroslog castings matches the average curve for the sand castings. The reduction-of-area values for the electroslog castings exceeded the values for sand castings.

13. On the basis of the data presented, the electroslog casting process has a potential for producing properties similar to those of wrought material for 2 1/4 Cr-1 Mo and 9 Cr-1 Mo steels and similar to those of sand-cast material for type 316 stainless steel. The electroslog casting process produces a better surface finish and casting interior (less porosity and fewer inclusions) than does sand casting.

## FUTURE WORK

The determination of mechanical properties of recently received electroslog castings from Cameron Iron Works and Selectrotech will continue. The creep testing of 2 1/4 Cr-1 Mo and 9 Cr-1 Mo castings currently in progress will be continued.

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SESSION III

APPLICATIONS AND TRENDS  
IN ELECTROSLAG WELDING

APPLICATIONS AND TRENDS IN ELECTROSLAG WELDING  
IN THE UNITED STATES

PRESENTED BY:

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MANAGER, WELDING ENGINEERING  
NEWPORT NEWS SHIPBUILDING

MARCH, 1985



The topic I have been asked to discuss this afternoon is "Application and Trends in Electroslog Welding in the United States." While I am aware of some of the work and applications of electroslog welding at other shipyards through the SP-7 panel, I am most familiar with that of Newport News Shipbuilding and speak from that point of view. In this presentation, I will briefly review our experience with electroslog welding. I will discuss (1) the use of the "plate crawler" and consumable guide processes in the construction of commercial ships, (2) our qualification and use of consumable guide welding on Naval ship construction, (3) the status of the SNAME SP-7 committee project on 4" - 24" thick multiwire consumable guide welding, and (4) our outlook on the future of the electroslog process.

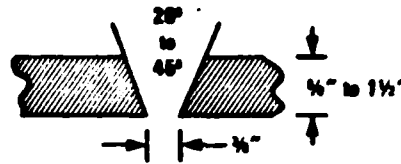
The largest use of electroslog welding at NNS was during the construction of three Liquified Natural Gas (LNG) tankers and two Ultra Large Crude Carriers (ULCC). During the construction of these ships, both the "plate crawler" and consumable guide versions of the process were used extensively and their use can be considered typical for construction of a commercial vessel.

The plate crawler version was used mainly for vertical butt welds in side shell and bulkhead plating. A single "vee" joint design was used as shown in Figure 1, with a 20 to 45° included angle and 3/8" root gap. This process was used for material from 5/8" to 1-1/2" thick. The process was highly efficient and deposition rates of 50 pounds per hour could be obtained. Typical parameters are also shown:

325 to 600 amps

32 to 45 volts

### PLATE CRAWLER



#### PARAMETERS

AMPERAGE  
(A)  
325 - 600

VOLTAGE  
(V)  
32 to 45

TRAVEL  
(IMP)  
1.5 to 4.5

DEPOSITION  
(lb/hr)  
Approx. 50

#### MECHANICAL PROPERTIES

TENSILE  
(PSI)  
65,000 to  
83,000

CHARPY "V"  
(ft lbs @ +14°F)  
WELD 48 - 54  
F.L. 37 - 68  
HAZ 41 - 145  
BM 111 - 162

BEND  
(2T)  
SATISFACTORY

Figure 1

Mechanical properties from the procedure qualification test on ABS grade CS base material (tested in the as-welded condition) are also shown:

#### Typical Base Material Chemistry

ABS Grade CS

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>
.16 max	1.00-1.35	.04 max	.04 max	.10-.35

#### Mechanical Properties

Tensile strength 65,000 - 83,000 PSI

Charpy "V" notch at +14°F

Weld 48-54 ft lbs

Fusion line 37-68 ft lbs

HAZ 41-145 ft lbs

BM 111-162 ft lbs

Satisfactory bend tests



Also seeing considerable use on these commercial ships was the single electrode consumable guide tube version. This was used primarily to weld the butt joints in the transverse frames. These welds were typically 3/4" thick and 30" in length. On the bottom shell, the equipment could be mounted on the face plate of the stiffeners. For stiffeners under main deck, holes were cut through the deck for the guide tube and the equipment was mounted on top of the deck.

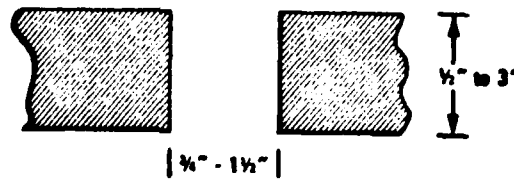
A square butt joint design was used with a 3/4" to 1-1/2" root gap as shown in Figure 2. Plate thicknesses from 1/2" to 3" can be welded with a single guide tube, but a maximum thickness of 1-1/2" was used in production. Typical parameters were:

275-560 amps

30-39 volts

which gave deposition rates of up to 18 pounds per hour.

### SINGLE WIRE CONSUMABLE GUIDE



#### PARAMETERS

AMPERAGE  
(A)  
275 - 560

VOLTAGE  
(V)  
30-39

DEPOSITION  
(lb/hr)  
Approx. 18

#### MECHANICAL PROPERTIES

ABS GRADE C (NORM)  
TENSILE  
(PSI)  
68,000 to  
71,000

CHARPY "V"  
(ftlbs at 32°F)  
WELD 28 - 39

BEND  
(2T)  
SATISFACTORY

ABS GRADE AM-36  
TENSILE  
(PSI)  
78,000

CHARPY "V"  
(ftlbs at +32°F)  
WELD 36  
F.L. 66  
HAZ 34 to 71

BEND  
(2T)  
SATISFACTORY

Figure 2

Mechanical properties on ABS grade C (normalized) material are:

Typical Base Material Chemistry

ABS Grade C (Normalized)

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>
.23 max	.60-.90	.05 max	.05 max	.10-.35

Mechanical Properties

Tensile strength 68,000 - 71,000 PSI

Charpy "V" notch at 32°F

Weld 28-39 ft lbs

Satisfactory bend tests

On ABS grade AH-36 material, the following properties were obtained:

Typical Base Material Chemistry

ABS Grade AH36

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>
.18 max	.90-1.60	.04 max	.04 max	.10-.50

Mechanical Properties

Tensile 76,000 PSI

Charpy "V" notch at +32°F

Weld metal 35 ft lbs

Fusion line 55 ft lbs

HAZ 34-71 ft lbs

Satisfactory bend tests

For thicknesses greater than 3 inches, multi-wire consumable guide tube electroslog can be used. It is an attractive process for heavy weldments such as rudder stocks, rudder posts, and shaft struts. When this type weldment is made using conventional bevels

and processes, large amounts of weld metal must be deposited. In order to control the final alignment of the parts, costly distortion monitoring and weld sequencing must be utilized. The electroslog process with its uniform shrinkage eliminates this expense. While there is considerable time for set-up and preparation, the reduced welding time offsets it. Welds that would take days to do manually can be electroslog welded in several hours. (See Figure 3.)

### ESW VS SMAW

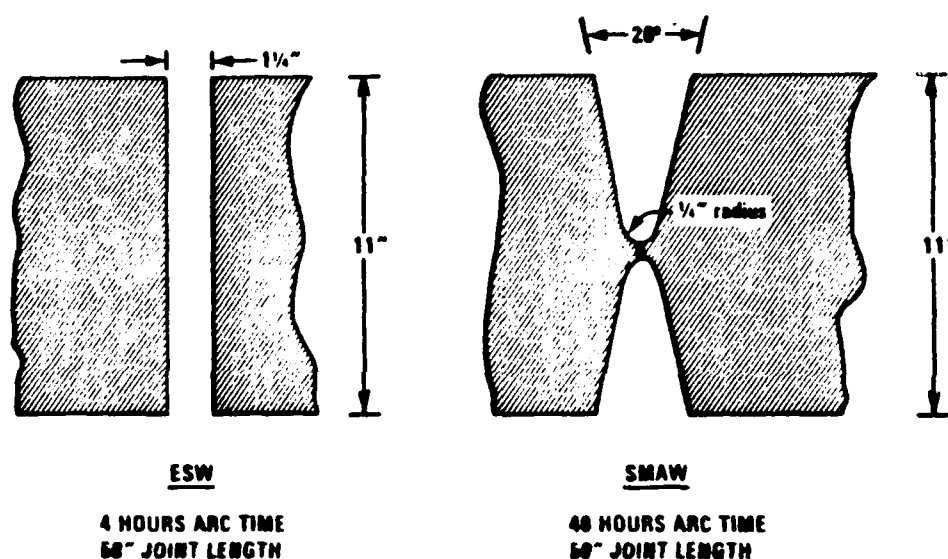


Figure 3

We are currently preparing to weld shaft struts for the aircraft carriers with the multiwire consumable guide tube process (see Figure 4). This shaft strut weld is 11" thick and approximately 48" long. Several mockups have been successfully welded and tested. The material of the strut is MIL-S-15083 grade B which has a 60,000 PSI tensile strength. Our approved technique uses three wires and oscillation.

Typical parameters are:

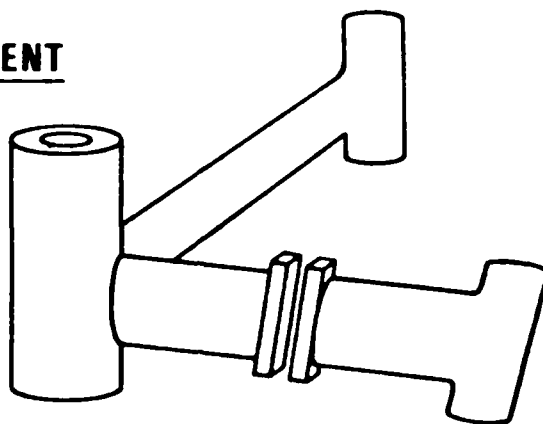
300-440 amps per guide tube

50-55 volts

1-3/4" - 2" oscillation amplitude

2-3 second dwell

### STRUT ARM WELDMENT



WIDTH APPROX. 11"

LENGTH APPROX. 48"

BASE METAL — MIL-S-15083 GRADE B

THREE GUIDE TUBES WITH OSCILLATION

<u>PARAMETERS</u>	AMPERAGE (AMPS) 300-440	VOLTAGE (VOLTS) 50-55		
<u>MECHANICAL PROPERTIES</u>	TENSILE (PSI) 70,000 to 73,000	CHARPY "V" (ft-lbs at +70°F) WELD 31.4 B.M. 14.2	BENDS (2T)	SATISFACTORY

Figure 4

### Typical Base Material Chemistry

Mil-S-15083 Grade B

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>
.30	.60	.05	.05	.60

## Mechanical Properties

Tensile strength 70,000 - 73,000 PSI

Charpy "V" notch

	<u>-20°F</u>	<u>0°F</u>	<u>30°F</u>	<u>70°F</u>
Weld	4.8 ft lbs	7.6	14.4	31.4
BM	3.2 ft lbs	4.2	6.4	14.2

Satisfactory bend tests

In order to use this process, it was necessary to cast additional material on the mating ends of the strut to provide a uniform cross-section for welding. This excess material will be removed after the weld is complete.

We also have underway a program sponsored by the SNAME SP-7 panel to develop techniques for welding material thicknesses from 4" to 24". The results of this program will be published in a reference document. Any shipyard desiring to use the process would not need to repeat the expensive development work but would be able to start with tested techniques. The document might include a table for selecting the proper number of guide tubes for the thickness being welded, recommended guide tube spacing, oscillation width, amplitude and dwell, as well as recommended parameters. Preparation set-up and operation instructions will also be given.

Successful welds have been made from 4" to 13" in thickness and work is in process for 16" to 24". The final report is scheduled to be completed in June of this year.

We have been experimenting with single wire plate crawler and consumable guide tube electroslag welding since 1971 and with

multiwire consumable guide since 1977. While the results have been generally acceptable, they have pointed out the fact that the process is best suited for material which does not have notch-toughness requirements. Notch-tough materials must have a post-weld heat treatment to restore the properties degraded by the high heat input and extremely slow-cooling rate of the electroslog process. Where post-weld heat treatment can be applied, even materials with high notch-toughness requirements, such as HY-80, can be welded by using electrodes which also respond to the heat treatment.

In the near future it is not likely that the use of electroslog welding will increase significantly. The process was most suited for commercial ship construction and that market is extremely slow. On the military side, there is an increased awareness and interest in notch-toughness properties which further limits the suitability of this process.

The multiwire process will continue to be a benefit to applications with thick cross-sections which can be heat treated after welding. When normalizing or quench and temper treatments can be applied after welding, the mechanical properties of the weld can equal or exceed those of the base metal. Where this treatment is used in place of a stress relief treatment, the added costs are minimal and the significant savings in welding time are still realized.

The biggest hurdle in the path of increased use of electroslog welding is the loss of notch-toughness properties in the Heat Affected Zone. It is possible to improve the weld

properties by filler metal selection but this has no effect on the (HAZ) base metal adjacent to the welds. If a method were found to reduce the degradation of the Heat Affected Zone, the electroslog process would see an immediate revitalization and substantial increase in utilization.





**APPLICATIONS AND TRENDS FOR ELECTROSLAG AND RELATED  
WELDING PROCESSES IN WESTERN EUROPE**

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**Paper presented at U.S. Navy Workshop on "Electroslag Processing for  
Marine applications."                      Annapolis                      5-6th March 1985.**



# APPLICATIONS AND TRENDS FOR ELECTROSLAG AND RELATED WELDING PROCESSES IN WESTERN EUROPE

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## 1. INTRODUCTION

Electroslag welding has long been recognised in Europe as an economical and highly productive technique for welding heavy section materials. It has been successfully used in many applications, e.g. longitudinal welds in pressure vessels, valve bodies and various structural applications such as blast furnaces, bridges, machinery parts etc. generally where toughness requirements are not severe, or where post weld normalising (or in some more stringent applications, double normalising) can be carried out to improve toughness.

The recent industrial recession, which has hit the European heavy engineering industries particularly hard, has led to a general decline in the use of the process in many areas, and this decline has probably been aided by a lack of confidence in the integrity of the welds, following recent problems in the U.S.A. with consumable guide welds in bridges, although no evidence of widespread microfissuring has been found in Europe.

The current use of electroslag and consumable guide welding in Europe is therefore restricted mainly to its traditional applications in pressure vessel and shipbuilding applications.

## 2. TYPICAL APPLICATIONS IN MARINE TECHNOLOGY

Shipbuilding is of course an obvious area where any mechanized vertical welding process can result in considerable economic benefits (1,2). Electroslag welding is widely used in European shipyards for butt welds in outer hull plates and bulkheads. For thicker steels, an elevator system is placed against the joint, on which are carried the control panel, welding head and welder. The power source, gas supply etc.. is normally located at the upper end of the weld.

Lighter weight apparatus can also be used for thinner steels on interior bulkheads and inner tank walls.

Recently, van Griensven (1) has indicated that the use of such techniques in the highly specialised Boelwerf yard in Belgium has resulted in very considerable time savings in medium to large scale ship production.

The use of consumable guide electroslag welding is usually limited to butt welds between longitudinal stiffeners, where the short weld length makes this process attractive. However, the poorer impact

properties when compared to electrogas have restricted its use to lower grade materials in less critical areas.

Marine applications are not restricted just to shipbuilding, and other applications of electrosag processes exist, or are under serious consideration in Europe. One of the most spectacular, but least publicized engineering projects in Europe is the Ooster-Schelde storm barrier, which consists of a combination of man-made islands and movable flood gates across the mouth of the Ooster Schelde in Southern Holland. This construction will protect the lowlands of Holland from the occasional very high tides which can exist in the Southern North Sea. The last major flood, in 1953, killed several hundred people in Holland, Belgium and England, where much of the coastal land is below sea level.

The flood gates (about 60 in all) consist of massive steel and concrete slabs which are raised and lowered hydraulically by huge pistons. These consist of tubular sections (~100 thick) ) of C-Mn steel which are electrosag welded and normalised. These sections are welded together by circumferential narrow gap submerged arc welding, to give piston rods approximately 15m long. The bores are subsequently machined to a very high tolerance. It is thus a marine application of electrosag pressure vessel technology.

One of the major industries in Europe is the development of the vast oil and gas reserves which exist beneath the North Sea. Plans now exist to develop the more northerly oilfields, in which the deep waters make the conventional steel jacket structure very expensive. One of the alternative platform designs which has been proposed is the Heerema tripod, which is essentially a single vertical column reaching from the surface to the seabed which is stabilised by three submerged legs, rather like a photographic tripod.

The walls of the central column and supporting legs will vary between 100-150mm, and will probably be made from a lower strength C-Mn steel. These column sections will be made by rolling plate sections to the appropriate shape, and electrosag welding the longitudinal seams, followed by normalising. The cylinder so formed will be welded end to end probably by submerged arc welding.

The use of electrosag welding in longitudinal welds of tubular structures for offshore structures has often been discussed, but although it is likely that the required toughness levels could be met, particularly for submerged joints, the process has never been implemented. The use of multi-power submerged arc welding, with and without metal powders, has been preferred. As it seems likely that accelerated cooled steels will eventually replace normalised steels in such applications, the use of electrosag welding would seem to be even less likely in future, as such steels would not maintain their strength after such high heat input welding and post weld normalising.

### 3. TRENDS IN EUROPE

The restriction on the use of electroslog welding is primarily a result of the low toughness encountered in the weld metal and HAZ regions. The weld metal problem can be overcome to a considerable extent by the use of suitably micro-alloyed consumables, generally containing Mo, Ti and B. Excellent results can be obtained from such consumables, due primarily to their fine microstructure, in which the principal constituent is acicular ferrite, and at least two major European consumable manufacturer's now market such consumables. Figure 1 shows a Charpy transition curve for electroslog weld metal in a 25mm thick C-Mn-Nb-Al shipbuilding steel, from which it is evident that properties suitable for most applications can be obtained (3).

Some effort has been made in Europe (4) to increase the toughness of the HAZ of electroslog welds by reducing the heat input. Techniques developed in Germany have achieved this by increasing the welding speed using additional wires (usually twice the normal number), and metal powder additions which can supply over 50% of the deposited weld metal. This can result in welding speeds of up to 24m/hr for 25mm plate, which is an increase in welding speed of more than one order of magnitude, and a reduction in energy input by a factor of about 2.

Results published by Eichhorn et al. (4) show significant improvements in HAZ toughness of C-Mn-Si-Al steels measured by the Charpy impact test at given distances from the fusion boundary. However, these improvements have been shown to be negligible when measured by the CTOD test (5). Detailed metallurgical investigation has shown that although high speed welding reduces the peak grain size and the width of the transformed HAZ, the differences in thermal cycle are insufficient to affect profoundly the microstructure of the coarse grained HAZ. Even with high speed welding, the coarse transformation structure remains almost unaltered. Typical examples of HAZ microstructures are shown in Fig. 2. It is therefore evident that real improvements in toughness must await further developments in steelmaking practice to produce steels which are resistant to high input welding. The TiN steels which were developed in Japan and to a lesser extent in Europe are a move in the right direction (6), but further improvements are necessary, since the TiN particles are not stable at very high temperatures, which results in very poor fusion boundary toughness.

A further practical observation on high speed welding is that the process tolerance decreases significantly as the speed increases, making careful setting up a prime requirement. The high welding speeds produce long weld pools which can be susceptible to solidification cracking, and these factors limit further improvements in welding speed, although the general reduction in C and S levels in modern steels may reduce the risk of solidification cracking.

To the author's knowledge, this type of system is not yet used

commercially, although it is clear that considerable potential exists when more suitable steels are available.

#### 4. CONCLUDING REMARKS

Electroslag and related processes serve a small but highly specialised and useful role in the European fabrication industry.

It is felt unlikely that the undoubted economic benefits of the process can be further utilised until steels with better resistance to high heat input welding are developed to allow acceptable HAZ properties without post weld normalising.

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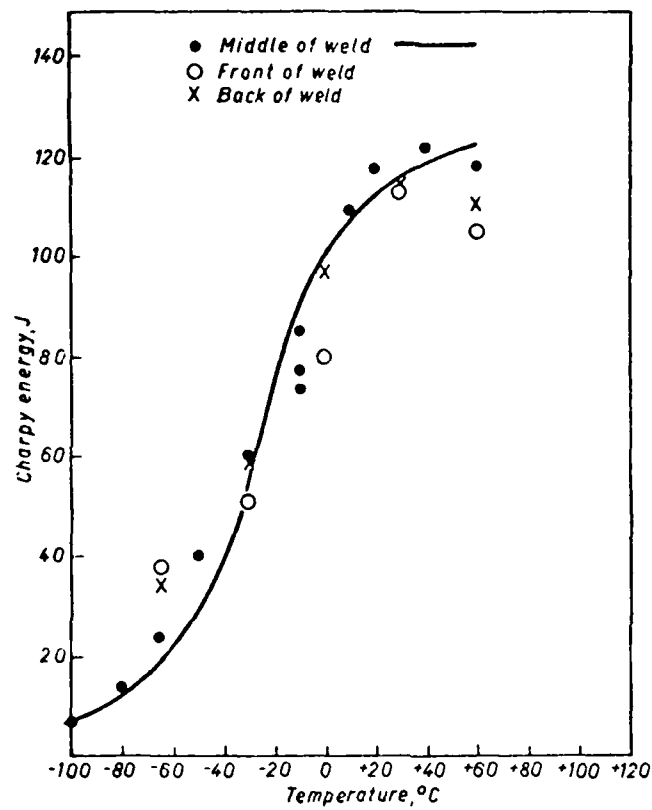
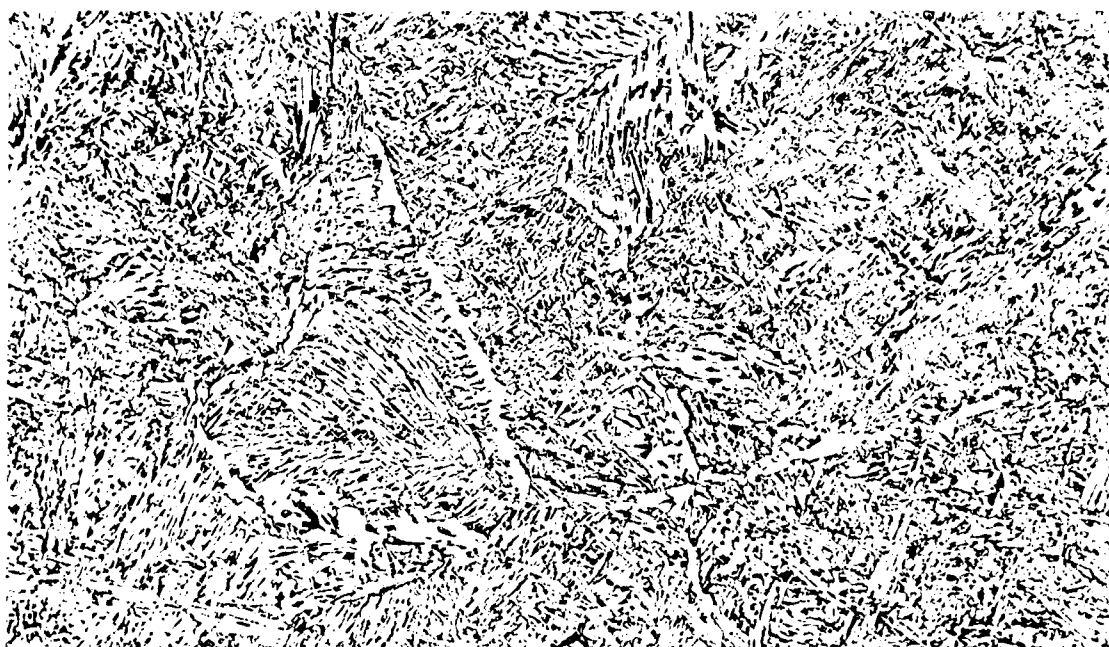


Fig. 1. Charpy transition curve for electros slag weld metal in a 25mm C-Mn-Si-Nb-Al steel, using a Ti-Mo-B alloyed weld metal (from ref. 3).



a)

X200 OM 3039



b)

X200 OM3032

Fig. 2. Comparison of HAZ microstructures in a 25mm C-Mn-Si-Nb-Al steel welded by

- a) conventional electroslog welding, heat input = 26 kJ/mm, welding speed = 2.2m/hr.
- b) high speed electroslog welding, heat input = 18kJ/mm, welding speed = 22m/hr.





ELECTROSLAG WELDING EXPERIENCE IN CANADA

by

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March 5, 1985

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## ELECTROSLAG WELDING EXPERIENCE IN CANADA

by B.A. Graville, Welding Institute of Canada

This brief note summarises some of the Canadian experiences in the use of electroslag welding.

Electroslag welding has been extensively applied in Canadian fabrication over the past twenty years in a wide variety of structures. Part of the credit for the success of these applications must go to the detailed attention paid to procedures and the parallel research and development program. At least one major fabricator has had a continuing R & D program on electroslag welding throughout this period.

The early part of the research program was devoted to practical aspects aimed at developing procedures and controlling the process in practice. This phase of the work included:

- . Procedures for very long welds using consumable nozzles (exceeding 12 feet)
- . Simpler shoe design that allowed for easy fabrication and lower material costs
- . Quick release clamp systems that avoided the conventional time consuming strongback methods
- . Procedures for varying thickness

- . Procedures for inclined plates
- . Methods of controlling distortion through the use of restraining blocks.
- . Detailed restarting and repair procedures (Fig. 1).

This work allowed successful application on such products as large pressure vessels, penstocks (unnormalized), blast furnaces, turbine runners and flange splices, column stiffeners and moment plates.

The use of electroslog welding for penstocks at Mica Dam showed several advantages:

- . Less skill required and easier training
- . More predictable distortion
- . All fitting could be done in a verticle position
- . Only one operator required
- . Defect rates of better than .1 percent were achieved
- . Cost effective even at 15/8 in. thick

Research was also devoted to extending the application of electroslog welding and several innovative processes were developed. A system for circumferential welding using the consumable nozzle method was proven successful (Fig. 2). A 4 ft. diameter shaft with a 6 inch wall thickness was welded in less than 4 hours with this method.

Electroslog welding was also extended to the flat position with development of lay down electroslog (Fig. 3). This allowed large groove or fillet welds to be made at high D position rates and in confined spaces. This method has not yet found practical application.

In the early 70's Canadian researchers became concerned about the origin of micro cracking in electroslog weld metal. Although this had generally been thought to be hot cracking, the possibility of hydrogen playing a significant role was explored. The role of hydrogen was dramatically demonstrated during a procedure qualification for one application in which tensile specimens were failing with zero ductility when tested in the as-welded condition. Because of the significant risk of hydrogen cracking in weld metal, a procedure involving retarded cooling using insulated blankets plus limited post-heat was evolved for welding a blast furnace. This was probably the first time such a procedure had been used for electroslog welding for hydrogen control and this was several years prior to the recognition of the role of hydrogen in the United States.

A major problem with electroslog welds that has drawn the attention of researchers, not only in Canada but around the world, has been the poor toughness. This means that electroslog welds are often normalized to improve toughness, thus limiting the application of the process both for economic reasons and to those components that can undergo a normalized treatment. Several approaches to improving toughness have been taken and it has been established that the use of special fluxes can substantially improve the weld metal toughness (Fig. 4). However, the limiting factor is the heat affected zone toughness. Research into narrow gap welding methods showed that even with a 60% reduction in heat input, heat affected zone toughness was not significantly improved (Fig. 5). Furthermore, the techniques required to achieve low heat input electroslog welds tend to remove the advantages for which electroslog welding is selected in the first place, e.g. fit up tolerance, simplicity and low training costs.

The double electroslog welding method (Fig. 6) developed in Canada was shown to significantly improve the heat affected zone properties although this process has not been applied in practice (Fig. 7). It essentially involves a two-pass method in which the first weld is cut out and re-welded such that the original heat affected zone is tempered by the heat from the second pass.

In recent years attention has turned to studying local normalizing as a way of extending the application of electroslag welding rather than changing the process itself. A local normalizing system would allow circumferential welds to be made and also be applicable in the field.

In summary, it may be said that Canada has enjoyed good success with electroslag welding in a wide range of applications that may be attributed, at least in part, to the attention paid to developing good procedures and ongoing research programs. Although the research undertaken to improve the properties has not had wide application, the work done on extending the process to more complex geometries has been more promising. This is because many of the methods used to improve properties make the process more complex. In many applications electroslag welding is now challenged by narrow gap arc welding methods, making it more difficult for electroslag welding to compete. It is believed that the future of electroslag welding lies in its ability to handle complex geometries and the use of automatic manipulation techniques, such as robotics, could offer some exciting potential for the future.

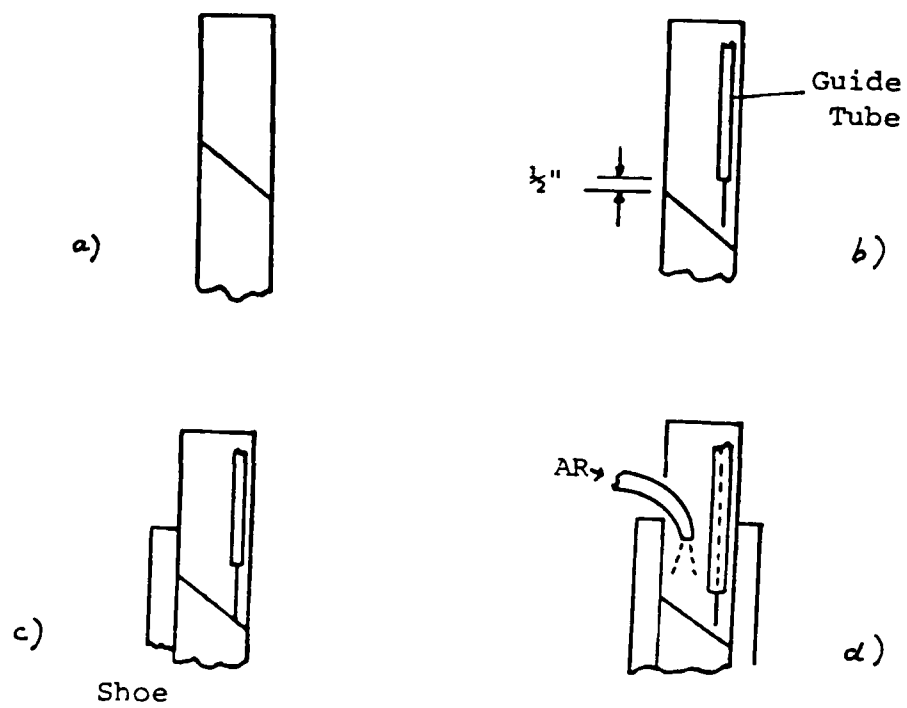


Fig 1. Restarting sequence

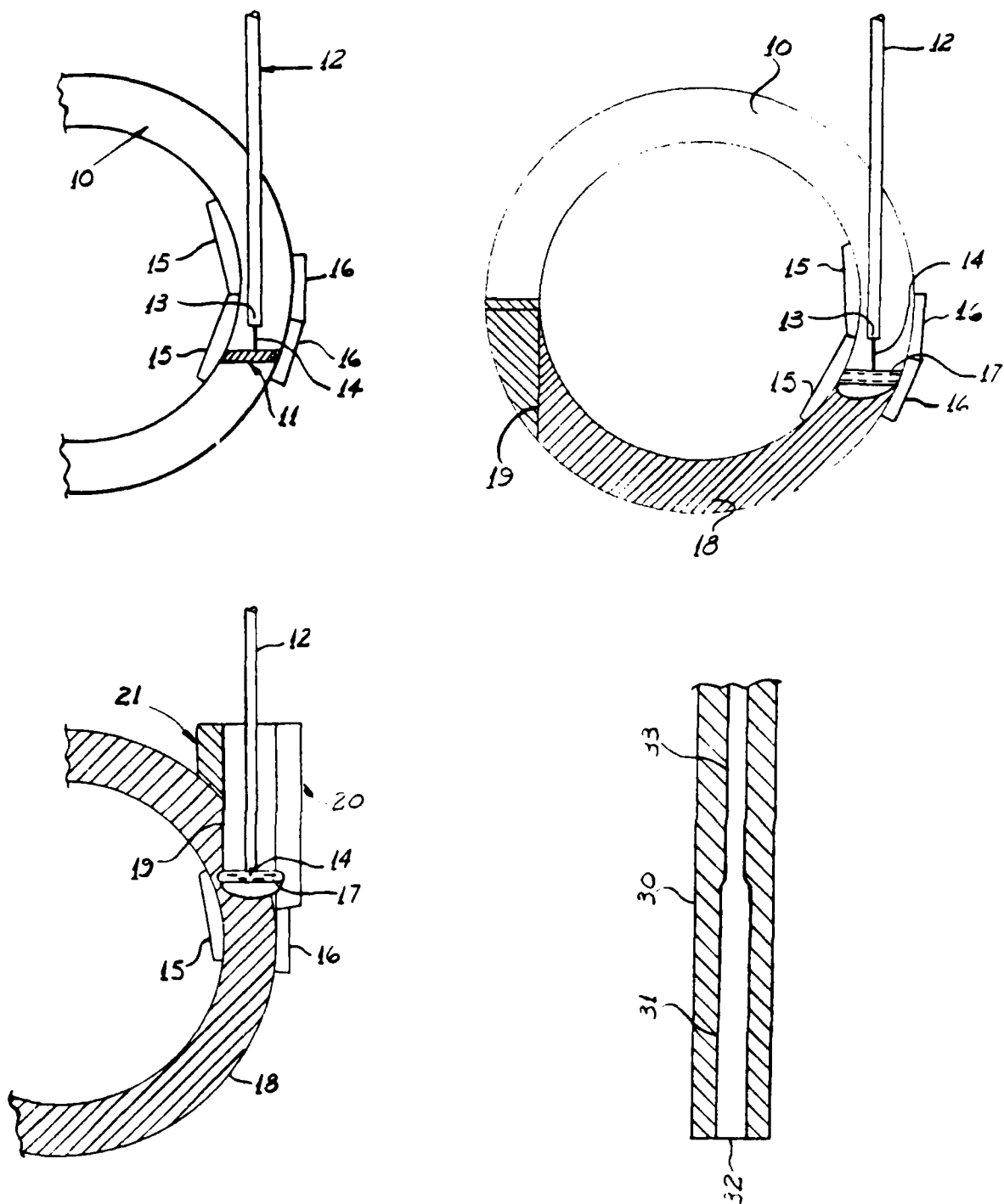


Fig. 2 Method for circumferential welds



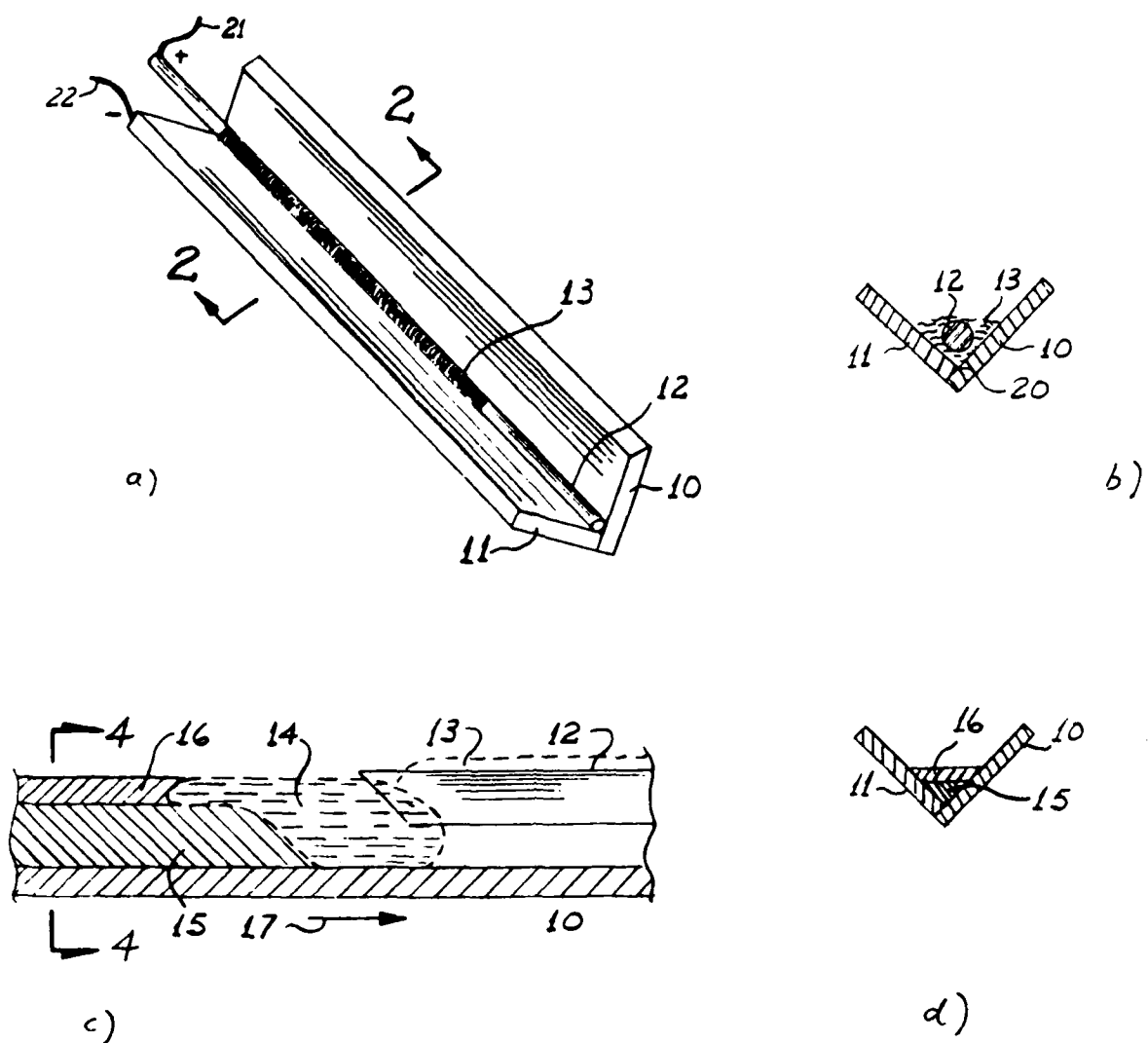


Fig. 3 Principle of lay-down electroslag welding

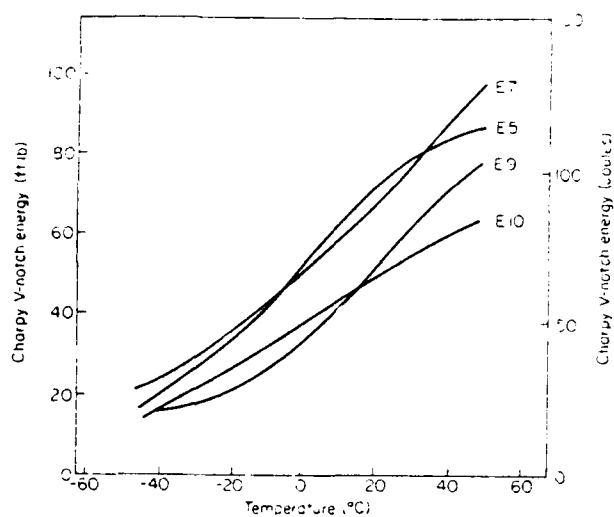


Fig. 4 Transition curves for weld metal from experimental fluxes

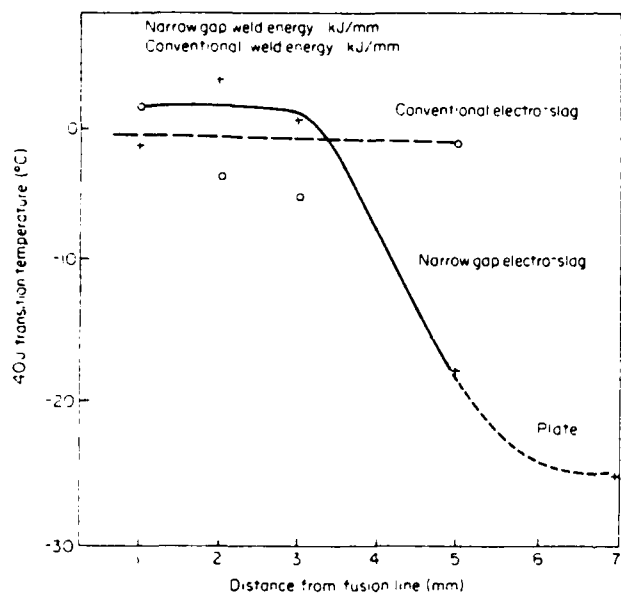


Fig. 5 Comparison of HAZ toughness of narrow gap and conventional electroslag welds

Fig. 5a 40J transition temperature

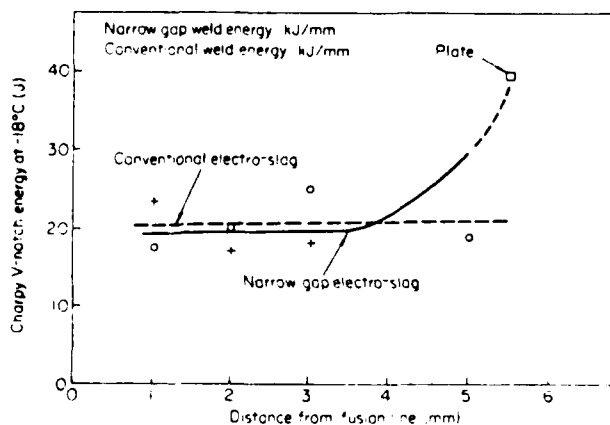


Fig. 5b CVN energy at  $-18^{\circ}\text{C}$

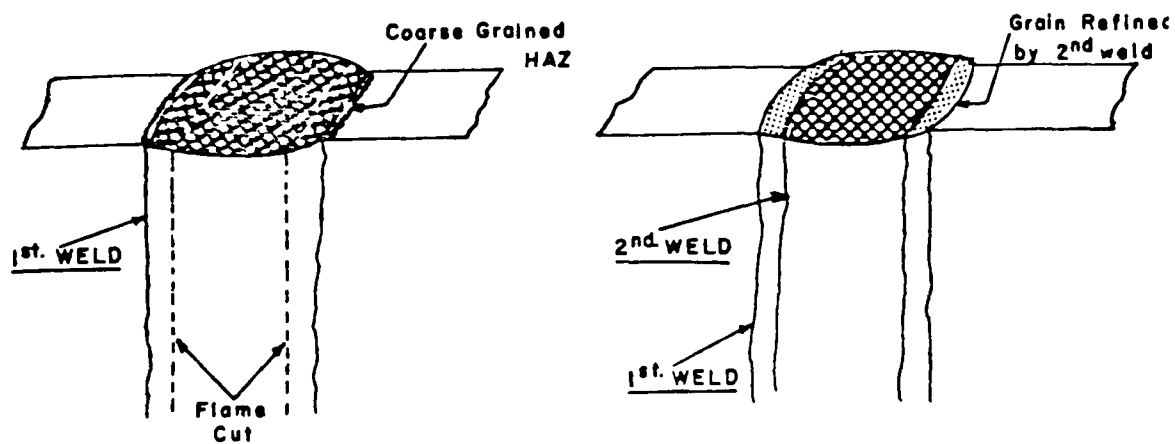


Fig. 6. Schematic representation of the Double Electroslag Welding Method

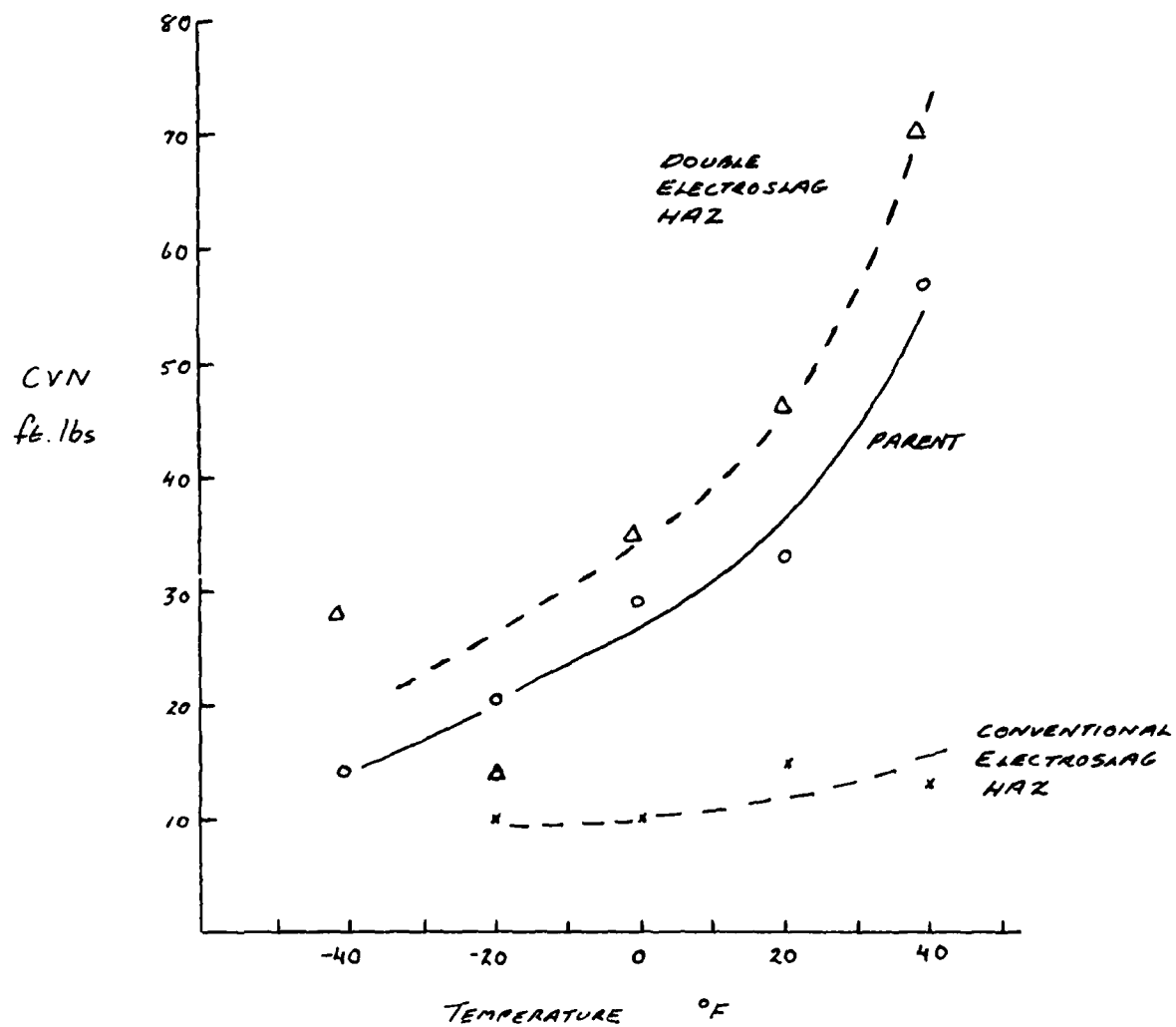


Fig. 7. HAZ toughness of conventional and double electroslag welds in A516 Grade 70 steel

## APPLICATIONS AND TRENDS OF ELECTROSLAG TECHNOLOGY IN JAPAN

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### ABSTRACT

Both electroslag welding, and to a lesser extent electroslag casting, have been applied in Japan on a wide range of steel products of varying size. Although the process works well, its use is declining due to increased use of electrogas and narrow gap welding processes and the greater utilization of high strength steels. Electroslag refining is being replaced with AOD and VOD processes due to economic advantages of these later processes. The only increasing use of electroslag technology appears to be in the area of overlay or cladding of pressure vessels, where the Japanese have developed a very efficient well controlled process.

### INTRODUCTION

Electroslag welding and casting processes have been used in Japan for approximately two decades, with generally good success. This report describes the amount of electroslag welding performed in Japan as reported in 1981 along with typical product applications. It also describes briefly an electroslag casting and an electroslag overlay process, as well as recent trends in the usage of electroslag technology. A brief discussion of the reasons for the trends is also included.

### ELECTROSLAG WELDING

Prof. Isao Masumoto of Nagoya University reviewed the application of electroslag welding in Japan in 1981.<sup>(1)</sup> His survey, which does not claim to be comprehensive, but appears to include most of the larger users of electroslag welding, indicates that more than 250 tons of electroslag weld metal was deposited in 1981. This was estimated to be 0.064 percent of the total volume of weld metal used in Japan; hence, in Japan electroslag is a specialized process which is used for a limited number of applications. Nonetheless, Japanese industry has a wide range of experience with the process. Welds of 0.3m to 9m length have been made in section thicknesses ranging from 16mm to 2.1m. Welding currents range from 280 amperes to 8,000 amperes with joint gaps from 18mm to 50mm. Materials welded include mild steel, high strength steel, stainless steel and Cr-Mo steels. As can be seen from Figure 1, three quarters of the weld metal is produced by the non-consumable electrode guide process and most of this is used by the industrial machinery and pressure vessel industries. It should be noted that these overall figures are heavily biased by several 2m X 4m x 50mm joints made in large castings for the industrial machinery industry. Each such weld contains over 10 tons of weld metal which is 4 percent of the total annual electroslag usage in Japan in 1981! Although, Prof. Masumoto's report does not indicate actual figures, it is believed that the shipbuilding and building construction industries produce the largest number of ESW joints, but these are of considerably smaller average size than those of the industrial machinery and pressure vessel industries.

Typical applications for electroslag welding in Japan include the following:

- i) Longitudinal stiffeners of the upper deck of ships (see Figure 2a)
- ii) Joining of large castings (see Figure 2 b, 2c, and 2d)
- iii) Longitudinal welds in cylindrical pressure vessels
- iv) Shells for blast furnaces and basic oxygen furnaces
- v) Corner joints and tee joints in building box columns.

It can be appreciated that most of these applications involve low strength steels (i, ii, iv and v). When higher strength steels are used or greater toughnesses are required, complete normalization is necessary (e.g. the water turbine in Figure 2d and the pressure vessel, iii). Indeed, the greatest limitation of electroslag welding in Japan is the poor fracture toughness of the weld heat affected zone. As a result, ESW is used only where toughness is not a concern, or where renormalization is not a prohibitive expense.

In the past few years, there has been much greater use of high strength steels in Japan (greater than 60 ksi yield strength). The high heat input of ESW is generally not acceptable for these steels and narrow gap and electrogas processes are being used. In a January 1985 summary of welding processes for 22 major industrial products, Mitsubishi Heavy Industries listed electroslag as a current process for only three products with a projection for the future that ESW will be used in only one application, viz. steel rolling mill stands. Narrow gap welding will replace ESW in both of the other current applications because it is becoming faster, cheaper, more amenable to repair and produces better weldment properties, than ESW.

Japanese welding experts are unanimous in their belief that the low fracture toughness of the weld zone is the greatest barrier to increased utilization of ESW in Japan. The second most difficult problem is repair of weld restarts, although this is a minor problem compared to the question of toughness. A former problem was hydrogen cracking; but, as in the United States, this has been solved by better process control.

Japanese investigators have tried a number of methods of reducing the toughness limitation. Process variations to reduce heat input, e.g. metal powder additions, reduced joint gap, multiple electrodes and the like, have been made, but are not deemed to be of sufficient magnitude or practicality to solve this problem. For some steels, the two-fold reduction in heat input permitted with electrogas welding is sufficient to improve toughness to acceptable limits, but for most steels, narrow gap is the best welding process which provides good toughness. In a few applications electron beam welding is preferred, but this process, like ESW, is very specialized.

In summary, Japan has a great deal of experience with electroslag welding of steels. The process works well, but the degradation of mechanical properties due to the high process heat input, limits ESW to a few specialized applications. Current trends indicate less use of ESW in favor of narrow gap, electrogas or electron beam processes. This trend is accelerated somewhat by the increased use of higher strength steels which have more restrictive heat input limitations.

#### ELECTROSLAG CASTING

Although there appears to be considerably less experience in Japan with electroslag casting as compared with electroslag welding, Mitsubishi Heavy Industries has considerable commercial experience with a process called "Yozo" which can be translated as "melt forming." Both large diameter pressure vessel cylinders or small diameter tubes can be produced by variations of this process as shown in Figure 3a and 3b. A number of interesting production materials and shapes have been made using this technology in

Japan. These include oval tubes of HK40 alloy, heavy section "H" beams of 25Cr-35Ni-2Mo heat resistant steel, bent steam reformer tubes of varying wall thickness and large diameter stainless steel elbows. The product quality is excellent. The only difficulty is that the electroslag casting process is relatively slow compared with alternative casting processes. With the advent of AOD and VOD refining techniques to steel casting technology, in recent years it appears that use of Yozo electroslag forming is rapidly declining for economic rather than for technical reasons.

As with electroslag welding, electroslag casting in Japan is declining; however, it is a technically sound process which may have a number of advantages in specialized applications.

### ELECTROSLAG SURFACING

One of the areas of electroslag technology where applications are increasing is surfacing. This process, called MAGLAY, was developed by Kawasaki Steel in the late 1970's and is now used extensively in Japan and has been licensed to several European manufacturers. As far as the Japanese know, there has been relatively little interest in this development from the United States.

The MAGLAY process is a strip cladding process in which high electrical conductivity flux (containing greater than 50 percent fluorides) is used to promote electroslag rather than submerged arc performance. This process was studied extensively in Europe in the early to mid 1970's but the major problem was undercutting at the overlap regions between weld deposits. Kawasaki Steel recognized that this undercutting was due to an unfavorable convection pattern in the liquid metal and slag. By introduction of external magnetic coils, they were able to alter the normal convection pattern and eliminate the undercutting, see Figure 4. The result is a very uniform weld overlay bead with exceptional smoothness. In addition, the low heat intensity of the electroslag process, as compared with the submerged arc process, greatly reduces dilution; which is an advantage in cladding width operations. The usual strip cladding with MAGLAY is 150 mm, but 300 mm wide coils have been used successfully. Since its introduction, some four or five years ago, MAGLAY has overtaken virtually all cladding operations in Japan. Submerged arc cladding is only used in some specialized operations where higher dilution is desired or on complex curvatures, such as conical heads. In these later cases, narrower beads must be used and the higher heat intensity of the submerged arc process permits more rapid travel speed. In most cases, where bead width is not restricted by vessel geometry, the MAGLAY process is preferred. The travel speed of MAGLAY is slower than submerged arc but the practical bead widths are greater.

### SUMMARY

Japanese industry has considerable experience with electroslag technology in a wide range of materials and product sizes. The process is generally considered to operate well, but its uses are declining in most cases. In the case of electroslag welding, the major disadvantage is the low fracture toughness in carbon and low alloy steels due to the high process heat input. Narrow gap, electrogas and in some cases electron beam welding processes are increasingly preferred due to lower heat inputs, similar costs and more versatile positional capability.

Electroslag casting in Japan has never been a major technology, but in recent years it has been nearly totally replaced by other processes which can refine the metal much more rapidly and economically. One exception is the MAGLAY electroslag surfacing process which has gained rapid acceptance in the pressure vessel industry.

There has been relatively little research on the electroslag process in Japan for nearly a decade. One exception is reference 6, which was apparently done in conjunction with development of the MAGLAY process. Indeed, some Japanese researchers questioned why I had performed research on ESW as late as 1980. As far as they were concerned it was a well understood but limited process of declining interest at that time. At a welding society meeting held in November 1984, attended by representatives of some 40 Japanese companies, only two companies noted current use of electroslag welding, and these two applications both involved joining of castings.

There is some interest, but no research experience, on electroslag technology for titanium in Japan. Kawasaki Heavy Industries and Mitsubishi Heavy Industries are competing for a contract to build a 2m diameter, 60mm thick spherical titanium submersible. The tentative welding process is electron beam, but the researchers were interested to learn that ESW may be a good process for titanium. In the area of electroslag casting, several Japanese steel companies would like to make large, rectangular titanium castings for production of rolled heavy section titanium plates. At present such work is only in the planning and basic research stage. It is not known whether electroslag casting of titanium would be considered for production of such shapes.

In conclusion, Japanese experience with electroslag technology is broad, but its use is declining in favor of other processes. There is no evidence that this trend will reverse in the future.

#### ACKNOWLEDGEMENTS

The author wishes to thank a number of Japanese researchers who have helped him gather information for this review. These include Prof. I. Masumoto of Nagoya University, Prof. K. Iida of Tokyo University, Dr. T. Kobayashi of the Japan Welding Engineering Society, Dr. S. Shono and Mr. G. Takano of Mitsubishi Heavy Industries, Dr. H. Nomura of Nippon Kokan K.K., Dr. H. Homma of Nippon Steel Corporation and Mr. S. Nakano of Kawasaki Steel Corporation.

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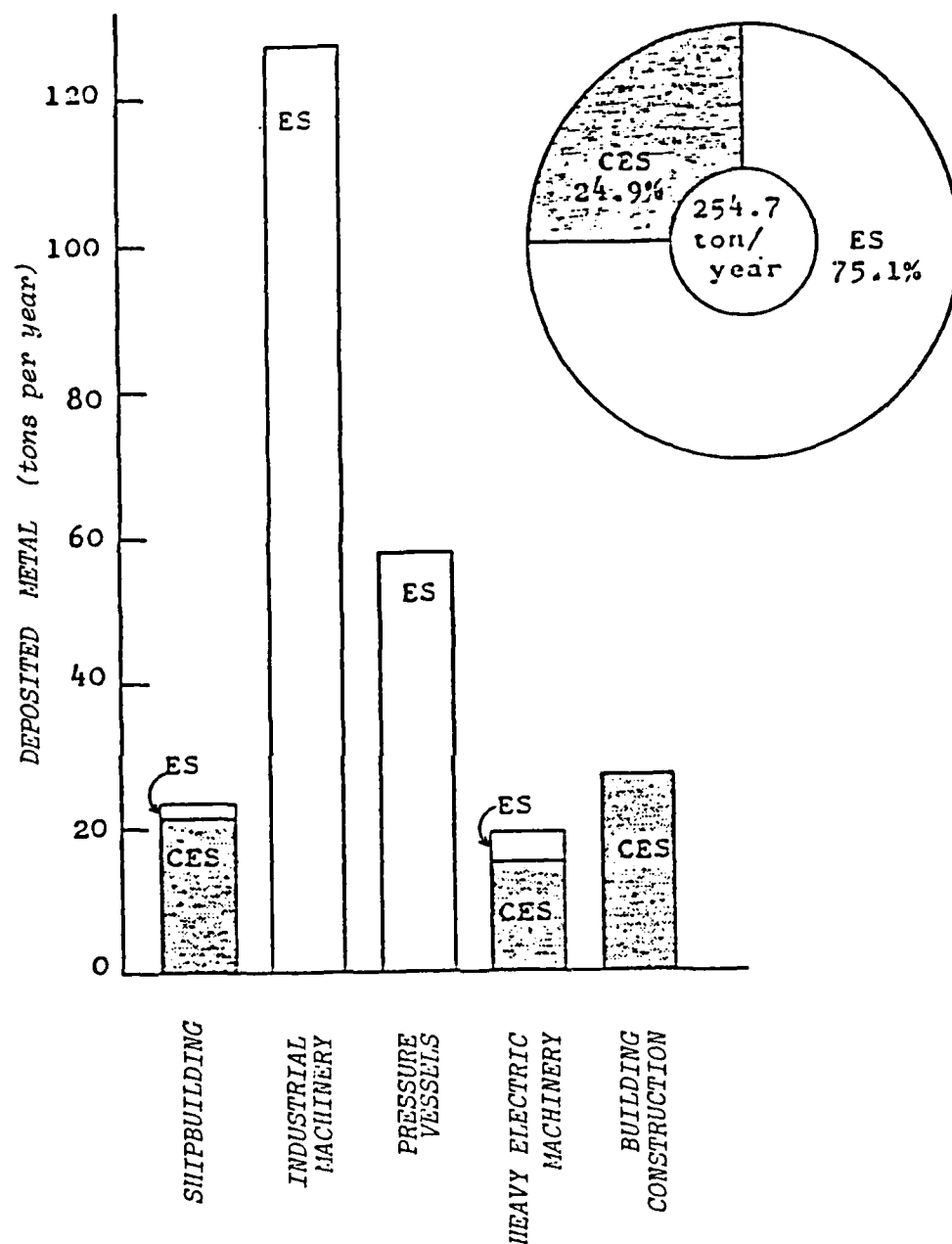
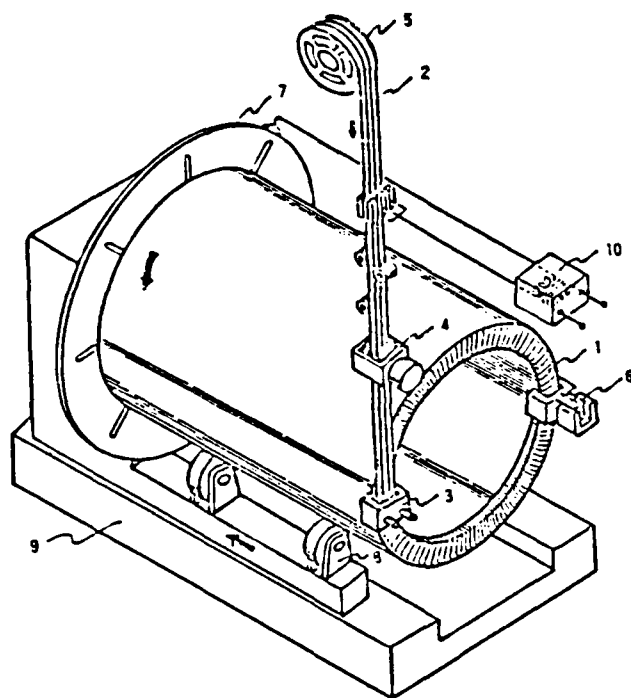


FIGURE 1. Weight of electroslag weld metal deposited in Japan in 1981. (Ref. 1)

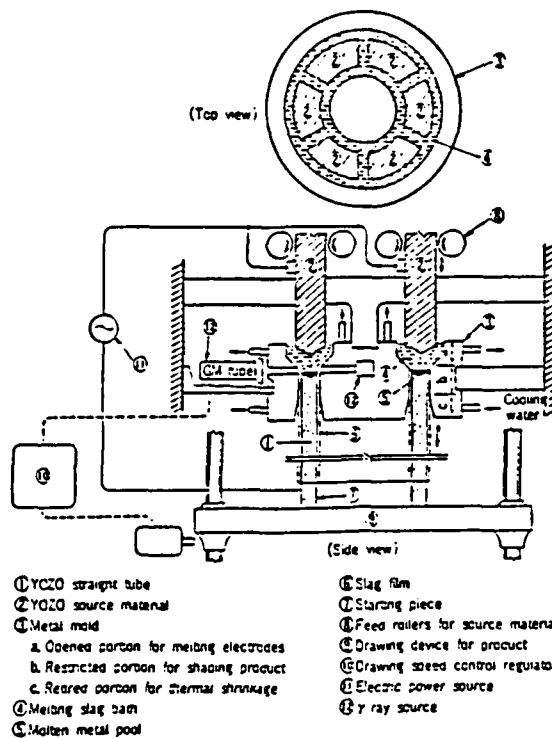
CES- Consumable guide process  
ES - Copper electrode guide process



1. YOZO tubular body
2. Source material
3. Box type mold.
4. Feeding device for source material
5. Reel
6. Shaping cutter
7. Turning table
8. Roller
9. Bed
10. Electric power source

Products : Shell barrel for pressure vessel

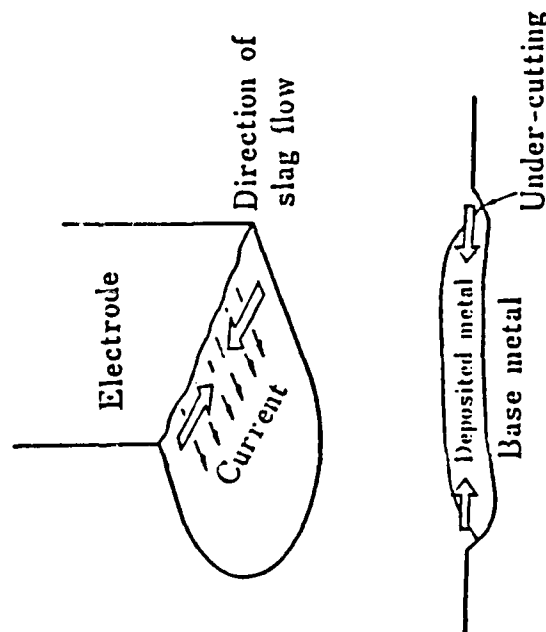
(A)



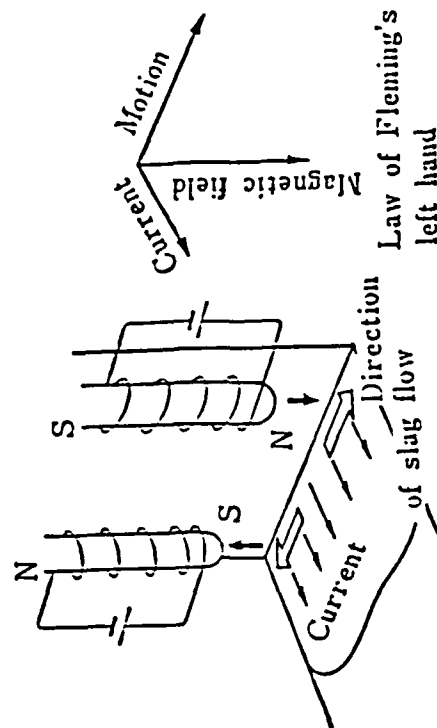
- ① YOZO straight tube
- ② YOZO source material
- ③ Metal mold
  - a. Opened portion for melting electrodes
  - b. Restricted portion for shaping product
  - c. Retired portion for thermal shrinkage
- ④ Melting slag bath
- ⑤ Molten metal pool
- ⑥ Slag film
- ⑦ Starting piece
- ⑧ Feed rollers for source material
- ⑨ Drawing device for product
- ⑩ Drawing speed control regulator
- ⑪ Electric power source
- ⑫ γ ray source

(B)

FIGURE 3. Examples of electroslag casting of tubular shapes by the YOZO melt forming process. (Ref. 3,4)



(A) Schematic mechanism of under-cutting caused by parallel welding current



(B) Control of slag flow with outer magnetic field

FIGURE 4. Principle of operation of MAGLAY electroslag surfacing process. Addition of electromagnetic coils alter the convection pattern and eliminate undercut. (Ref. 5)



## SOME TRENDS IN ESW RESEARCH IN THE U.S.S.R.

by Dr. V. Malin

ESW, developed more than 30 years ago by Paton Institute, has been widely used in all developed countries of the world ever since the Soviet Union exposition on ESW received the Grand Prix award at the 1958 Brussels World Fair.

Assessing state-of-the-art of ESW, it should be noted that there are two major areas of application. ESW of relatively thin (2 in. max.) and thick (higher than 2 in.) metals.

ESW of thin metals is widely and routinely used in the Soviet ship building industry. Almost all ship yards use electroslog welding for the vertical butt welds of the ship hulls when the thickness exceeds 3/4 in. Thinner walls are often welded by electrogas flux-cored arc welding using CO<sub>2</sub> shielding gas.

Unlike in other countries, ESW in the Soviet Union is performed using preferably alternating current and drooping volt-ampere characteristics of the power supplies. The fluxes used are mostly of the basic types to improve mechanical properties of the welded joints.

Relative to thick steels, ESW of thin steels presents much less problems from the metallurgical point of view. The main problem is to provide productivity which could justify that over other welding processes, taking into account the differences in part preparation and assembling operations.

Let us identify some relatively new trends in research of ESW

resulting from common problems encountered in ESW of low carbon and low alloyed steels.

1. The search is going on for an optimal ESW method to improve quality and mechanical properties of the ES welds and ESW productivity. Among the relatively new directions are investigation of ESW with different kinds of filler metal additions, such as powder addition to reduce grain size, addition of a hot flux cored wire to improve chemical uniformity of the different portions of the weld, armoring the weld with lumpy filler materials to increase productivity and improve thermal cycle, and addition of the cold filler wire in the center of the weld puddle for disorientation of the grains.
2. Thermal cycle regulation during ESW to reduce overheating of the steel. The techniques include preferential cooling of the high temperature zones of the solidified weld and slag pool, current modulation, adaptive control of welding parameters according to gap variations, application of transverse magnetic field to distribute heat flow more evenly and improve hydrodynamic processes in the weld puddle, cold filler metal additions, and gap reduction.
3. Residual stress reduction by special methods of balanced heating.
4. Metallurgical reactions in the HAZ are studied, namely,
  - a) the zone heated above 1350-1400°C with smaller grain size where  $\gamma - \delta$  ferrite transformation takes place. This is associated with chemical segregation effect and eventually with mechanism of crack initiation;

- b) zone with large grain size, which is also associated with brittle fracture of the HAZ;
  - c) grain borders.
5. Base metal, fillers and flux composition optimization to withstand solidification cracks and tear, delayed cracks and lamellar tearing. For example, for Cr-Ni-Mo steels, investigation is being conducted in the direction to optimize contents of Mn, S and C. Lamellar tearing is found to be reduced when ductility in the through-thickness direction is improved by using steels made by ES casting process.
6. Development of low-alloyed steels, specially designed for ESW, which require no post welding heat treatment. The principles on which this development is based are the following:
- a) Limitation of C by 0.10-0.12% to suppress formation of the overheated structural zones responsible for toughness reduction;
  - b) Grain size reduction by microalloying the steel with aluminum nitrides or boron;
  - c) Macroalloying the steel with the elements which improve the cleanliness of the grain border (Ce, for example);
  - d) Limitation of the elements which form carbides on the grain borders (Ti, Zr).
7. Development of mathematical models for ESW and methodology to facilitate calculation of the:

- a) thermal cycle in the various zones of the weld and HAZ, and welding parameters required to provide the selected thermal cycle;
- b) distortion of the low-alloyed steels taking into account phase transformation of the metal;
- c) admitted defects in the weld based on base and weld metal composition, properties required, nature of the external load, size and location of the defect, etc.

In conclusion, it should be noted that in recent years ESW has been successfully challenged by the competitive welding processes and techniques. The most promising of these are electron-beam and narrow gap welding.



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ELECTROSLAG PROCESSING FOR MARINE APPLICATION SUMMARY  
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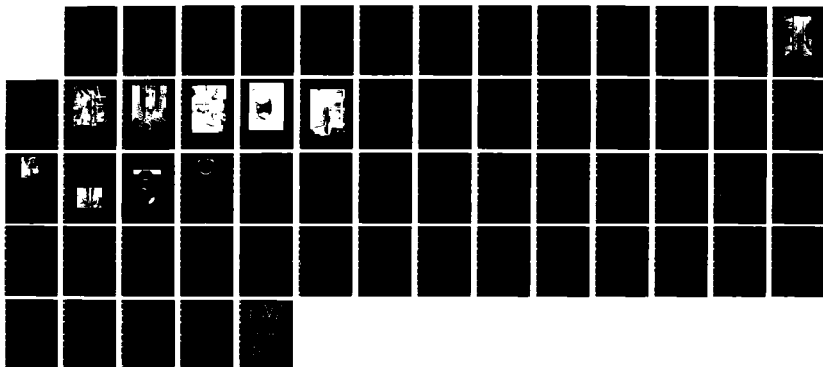
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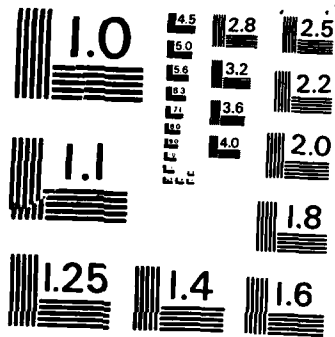
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SESSION IV  
APPLICATIONS AND TRENDS  
IN ELECTROSLAG CASTING

DOMESTIC APPLICATIONS AND  
TRENDS IN ELECTROSLAG CASTING

Presented By:

Mr. M. Hobday  
United States Department of Energy



## DOMESTIC APPLICATIONS AND TRENDS IN ELECTROSLAG CASTING

### Introduction

The Department of Energy through the Morgantown Energy Technology Center (METC) has been sponsoring work in electrosag casting (ESC) since January 1981. This work as well as some previous work sponsored by the Department of Energy (DOE) will be described. Advantages of ESC, barriers to commercialization, existing facilities, and future plans will be discussed. Detailed results from the METC-sponsored work will be presented in a companion paper by Vinod Sikka of Oak Ridge National Laboratory.

### Background

DOE first sponsored work in ESC in 1979 when a project was established with Mellon Institute of Carnegie-Mellon University, Pittsburgh, Pennsylvania, and G. K. Bhat as principal investigator. Using an ESC facility capable of producing castings 16 inches in diameter and weighing 1,500 pounds at Champion Steel Company, Orwell, Ohio, castings were made in molds lined with copper or carbon steel. A conclusion from the work (Bhat 1982) was that ESC valve bodies made of carbon steel that require only minor machining to reach final or net shape can be produced for less than \$0.27 per/lb in 1982 dollars.

In 1982, a follow-on project was initiated to examine ESC as a lower cost alternative than forgings for making components for coal gasification plants. The four major goals for the project are improving the process, data gathering to support ASME code approval, transferring technology, and fostering industrial experience with manufactured pilot components. As the project developed, castings became available from three sources for evaluation: Selectrotech, Pittsburgh, Pennsylvania; University of British Columbia, Vancouver, Canada; and Cameron Iron Works, Houston, Texas. Oak Ridge National Laboratory, Oak Ridge, Tennessee is evaluating the castings from all three sources and managing the project. Mellon Institute is investigating improved mold design and other process improvements such as the addition of powdered or molten metal. Through continued cooperation with Cameron Iron Works, a pilot component will be manufactured. Progress from this work has been reported previously through a DOE-sponsored symposium in June 1983 (Judkins and Hobday, 1984).

### Advantages of ESC

ESC is a near-net shape process that would compete with forgings, sand castings, and powder metallurgy as a method for manufacturing shaped components such as valve bodies, pump housings, shaped pipe fittings, compressor cylinders, and similar components. ESC has the following advantages:

- Components can be fabricated from materials that cannot be forged because of their strength, brittle nature, etc.
- Reproducible mechanical properties are obtained as shown in Figure 1 where a data band 40 MPa wide will include data from three separate castings.

- Isotropic mechanical properties are obtained. This is also shown in Figure 1 where the maximum difference in data from longitudinal and transverse samples is 50 MPa.
- Conventional casting defects are reduced. ESC has less shrinkage, porosity, and chemical inhomogeneity than sand castings.
- Properties comparable to forged products are obtained with ESC. Figures 2 and 3 show data for 2½ Cr-1 Mo castings that are equal or better than the average values for forging of the 2½ Cr-1 Mo steel.
- Economics favor ESC. The capital cost of ESC facilities are orders of magnitude cheaper than forging facilities. It has been estimated (Mitchell, 1984) that \$1.40/lb (about 50 percent) can be saved on a 500 lb product by using ESC rather than sand casting. The absolute savings may be questioned, but there is little doubt that ESC has favorable economics when compared with sand castings or forging processes.

Table 1 shows a comparison of several near-net shape processes with a list of ideal process features. The processes were ranked one through four, with one being the best, for each feature and equal ranking was given to processes where differences could not be determined. All features in the comparison were given equal weight; however, for specific applications, some features may be so important and others so insignificant that a different list of ideal features would result. The table is provided primarily as a concise way of comparing the features of competing technologies. It also provides a clear indication of ESC's potential for producing shaped components.

#### Obstacles to Commercialization

The obstacles to commercial use of ESC were discussed at a symposium (Judkins and Hobday, 1984) held in June 1983 in Morgantown, West Virginia among representatives of Government and industry. This group proposed the following reasons for the lack of commercialization of ESC in this country.

- The low demand for forgings and general business climate make initiation of new technology difficult.
- Business managers need to be educated to accept a new technology.
- ESC is done in Germany, Italy, Japan, China, and the U.S.S.R, however, the economics of these operations are unpublished and are not transferable to domestic conditions. Mold costs are intertwined in the overall economic question.
- The reproducibility of large (1 ton or greater) castings is not proven.
- ASME code qualification is needed to open the market for pressure-containing parts that are usually forged.

A few of these barriers to commercialization can be overcome by independent Government research, but they can be better overcome by a cooperative program with private companies in cooperation with the Government.

### Available Facilities

There are five operational ESC facilities in North America. Canadian facilities include one at the University of British Columbia (UBC), Vancouver, and one at the Canada Centre for Mineral and Energy Technology (CANMET), Ottawa. In the U.S, facilities are located at Selectrotech, Inc., Pittsburgh, Pennsylvania; Cameron Iron Works (CIW), Houston, Texas; and the Oregon Graduate Center, Beaverton, Oregon. Figures 4 through 10 are pictures and schematics of some of the facilities.

The UBC (Sikka and Mitchell, 1984) facility is capable of making 1 ton castings, and has been in operation for several years. A variable speed chain drive moves the water-cooled electrode holder on aluminum rail guides at speeds from 0 to 6.5 inches/min. The drive, holder, and guides are suspended in a steel I-beam framework. A 250 KVA transformer provides power to the system which can cast maximum cross sections of 10 inches by 10 inches. The control panel is simple, showing the primary and secondary current, the secondary voltage, a counter to show electrode travel, and a multichannel temperature indicator for monitoring the cooling water.

The facility at CANMET (Buhr 1985) is about 3 years old and has both single electrode and multiple electrode capacity. The single electrode design is patterned after the unit at UBC except it has a 300 KVA transformer. The multiple electrode unit was designed at CANMET and can handle four electrodes powered by four AC welding transformers rated 1,000 amps each. The single electrode unit can handle a 5-inch diameter electrode and cast a 1,500-lb part. Castings are limited to about 10 inches in diameter and 4 feet in height.

Cameron Iron Works' facility is also patterned after the one at UBC. Power is provided by a 250 KVA transformer. Electrodes up to 4 inches in diameter can be used to produce castings up to 500 lb and 10 inches in diameter. With this arrangement, CIW could achieve melt rates of 360 lbs/hr (Judkins 1984).

Selectrotech's facility shown in Figures 8 and 9 are of a much heavier construction than those previously described. This unit can accommodate 12-inch diameter electrodes to produce 16-inch diameter round or 15-inch square castings weighing  $2\frac{1}{2}$  to 3 tons. Melt rates of 400 to 800 lb/hr can be obtained with this unit powered by a 600 KVA transformer. Parts of this facility came from the facility constructed earlier at Champion Steel which is no longer available.

Figure 10 shows the facility at the Oregon Graduate Center. This unit powered by a 600 KVA transformer is capable of casting 12 inch diameter rounds 6 feet long. Cylindrical ingots of 2,000 to 3,000 lbs have been cast at this facility (4) which is an ESR facility obtained from ESCOE.

### Future Activities

The current project work is planned to continue through FY 86. By the end of that time, 19 castings from three different suppliers will have been thoroughly characterized. The castings will consist of a low-chromium steel ( $2\frac{1}{2}$  Cr-1 Mo), a medium-chromium steel (modified 9 Cr-1 Mo), and a high-chromium steel (CF8M-316 SS). Step castings and valve body shapes are included in this project. One pilot component, probably a valve, will be fabricated and placed in service.



## Summary

ESC has potential as a technique for manufacturing relatively complex shapes for use in demanding applications. The technical feasibility has been demonstrated. Education of manufacturers, an improved cost base, and code approval are areas that still need support to advance the technology. This can possibly be best accomplished by industry or by industry in cooperation with one or more Government agencies. Manufacturing components that do not require code approval and are difficult to manufacture by other techniques are probably the best place to begin commercialization.

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- Conversation with R. Buhr of Canada Centre for Mineral and Energy Technology. February 15, 1985.
- Conversation with R. Judkins of Oak Ridge National Laboratory. February 21, 1985.

TABLE 1 COMPARISON OF NEAR NET SHAPE PROCESSES

IDEAL PROCESS FEATURES	FORGING	SAND CASTING	POWDER METALLURGY	ELECTROSLAG CASTING
LOW CAPITAL COST	4	2	3	1
LOW OPERATING COST	4	2	3	1
ISOTROPIC PROPERTIES	3	4	1	2
ISOTROPIC COMPOSITION	1	1	1	1
WIDE RANGE OF PART SIZE	4	1	3	2
MINIMUM SHAPE RESTRICTIONS	4	1	3	2
WIDE RANGE OF MATERIALS	3	2	1	2
LOW POROSITY	1	3	4	2
NEAR NET SHAPE	4	3	1	2
SURFACE FINISH	4	3	2	1
REPRODUCIBLE PROPERTIES	1	4	2	3
CODE APPROVAL	1	2	4	3
PROPERTY ENHANCEMENT	1	4	4	2
MECHANICAL PROPERTIES	1	3	4	2
TOTAL	36	35	35	26
RATIO TO IDEAL	2.57	2.50	2.50	1.86

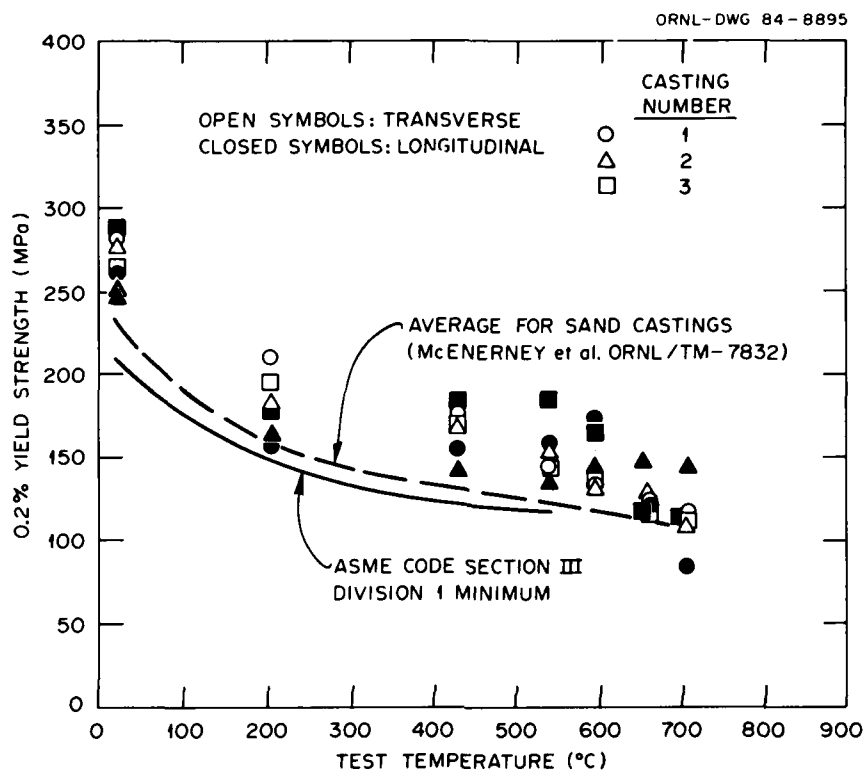


Figure 1. Yield strength of electroslag castings are compared to show the reproducible and isotropic mechanical properties that are obtainable. (Sikka 1984)

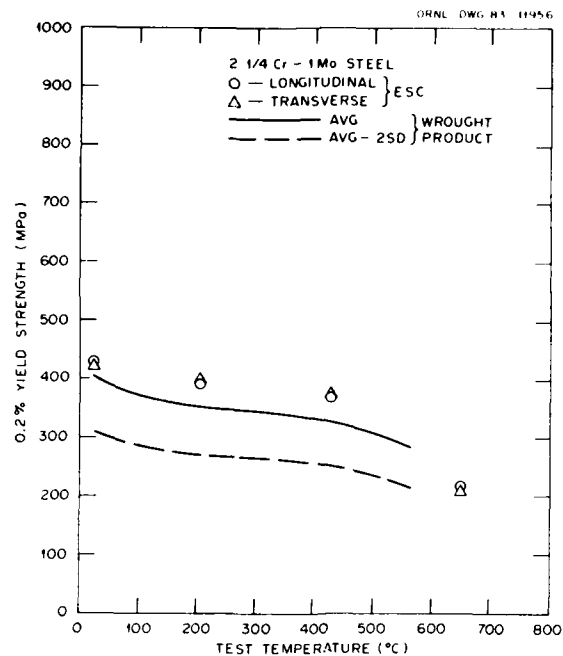


Figure 2. Comparison of yield strength (0.2 percent) of electroslag cast 2 1/4 Cr-1 Mo with the average and average minus 2 standard deviation curves for the wrought material tested in the normalized-and-tempered condition (Sikka, 1984).

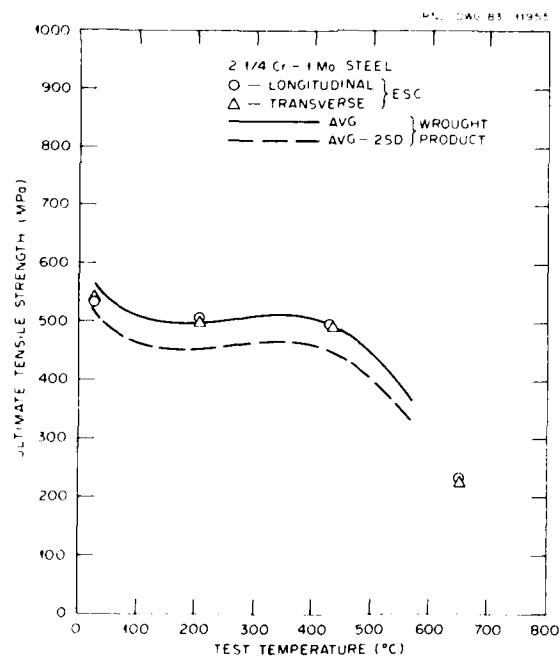


Figure 3. Comparison of ultimate tensile strength of electroslag cast 2 1/4 Cr-1 Mo with the average and average minus 2 standard deviation curves for the wrought material tested in the normalized-and-tempered condition (Sikka, 1984).

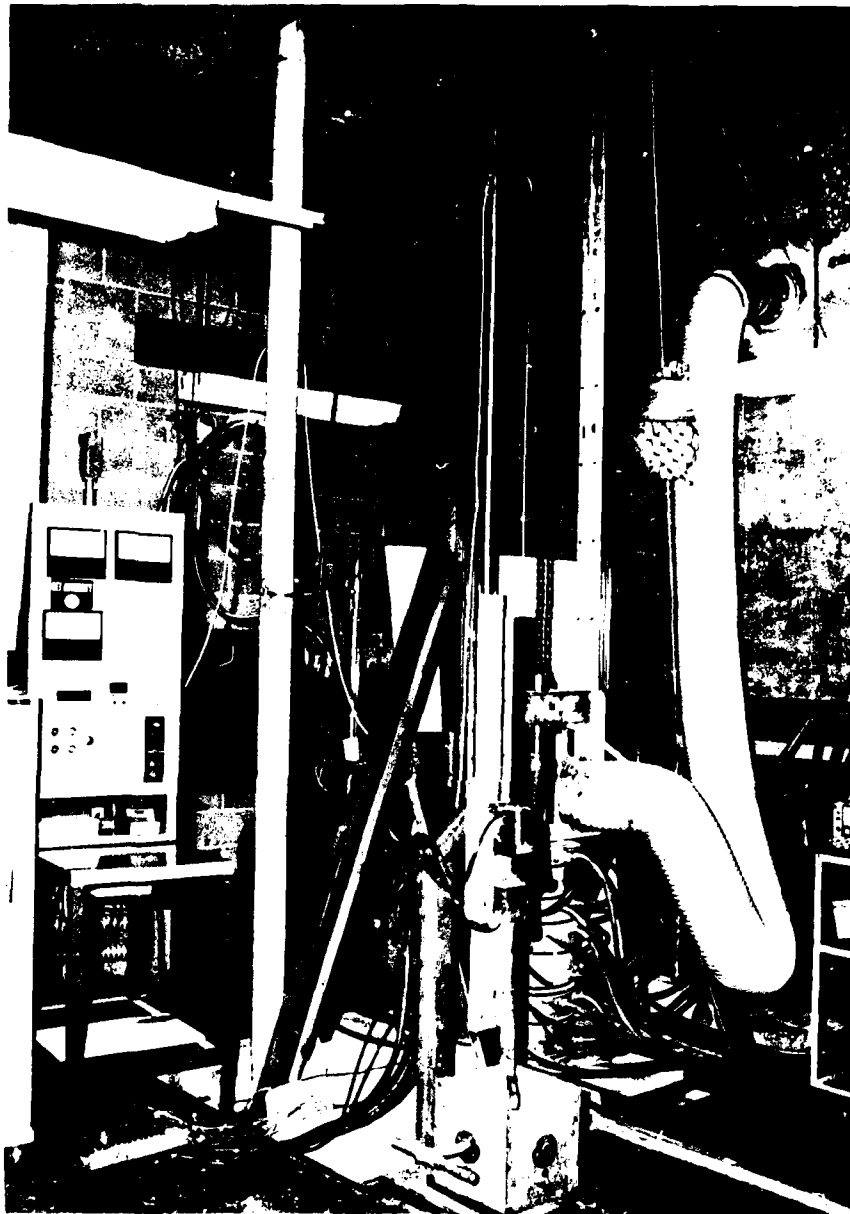


Figure 4. Overall view of the electroslag casting installation at the University of British Columbia. University of British Columbia photograph.

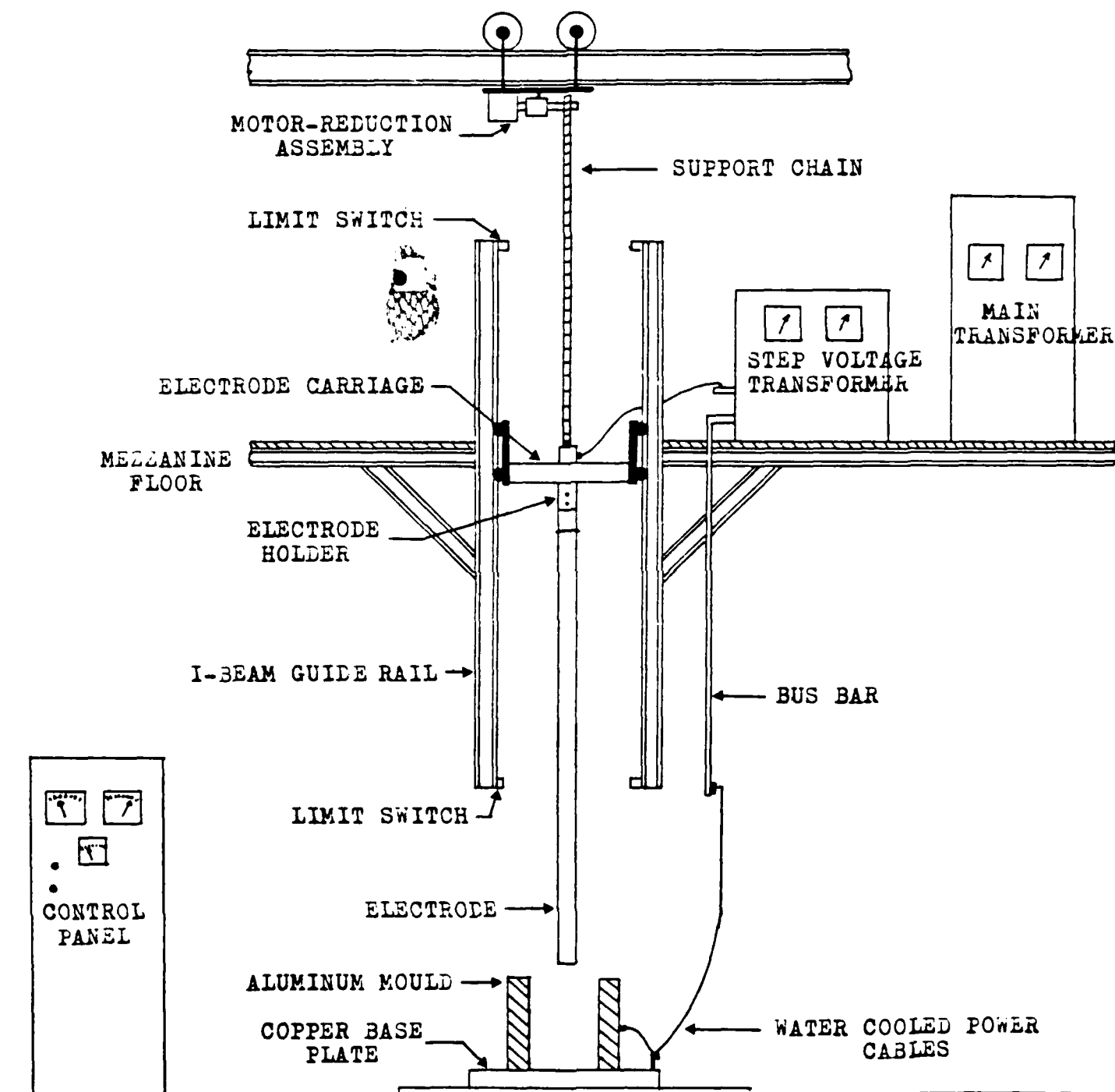


FIGURE 5: SCHEMATIC OF ESC SET UP AT CANMET  
(Furnished by CANMET)

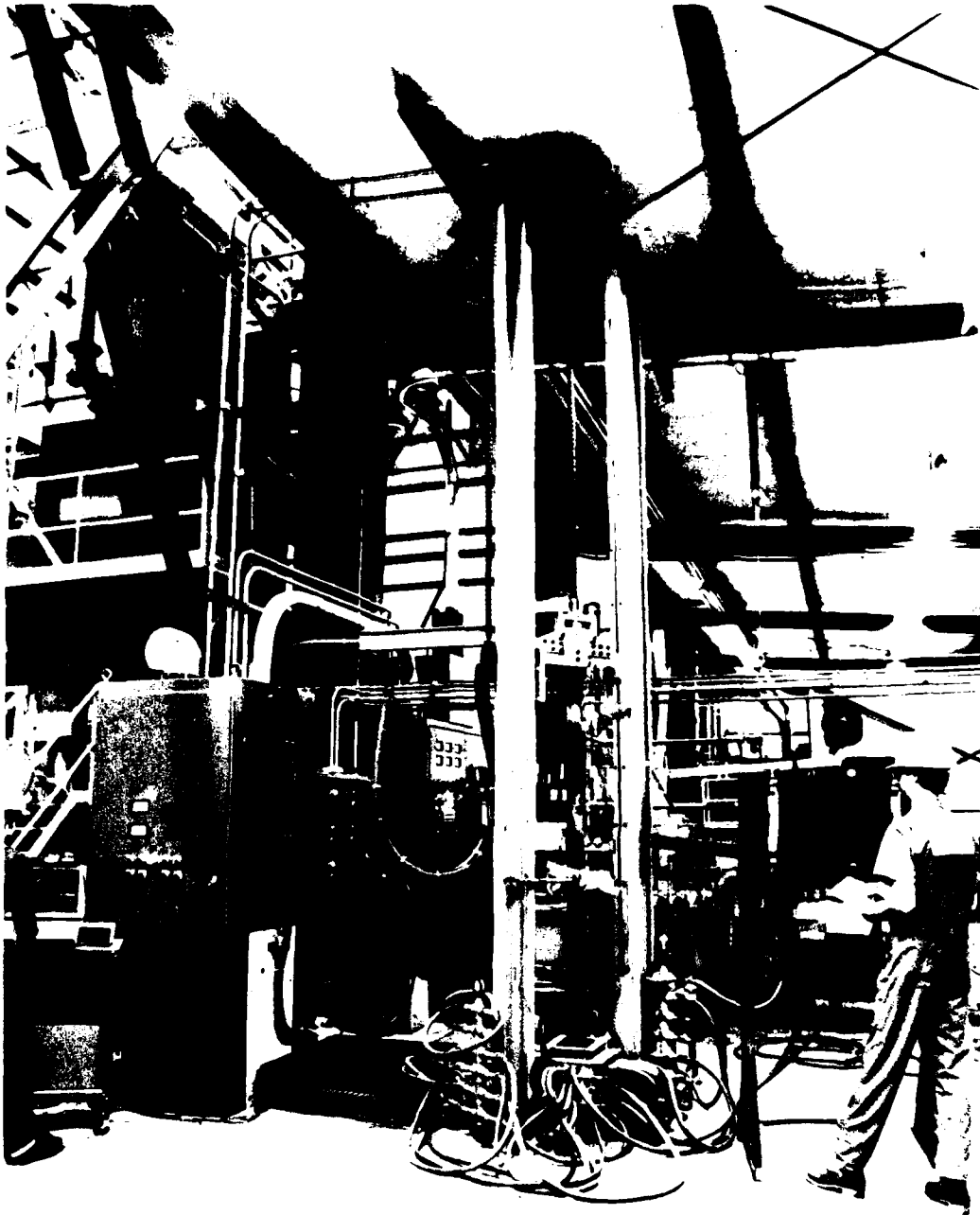


Figure 6. Overall view of Cameron Iron Works ESC Facility (Courtesy of Cameron Iron Works).





Figure 7. Close-up view of mold in Cameron Iron Works  
ESC Facility (Courtesy of Cameron Iron Works).

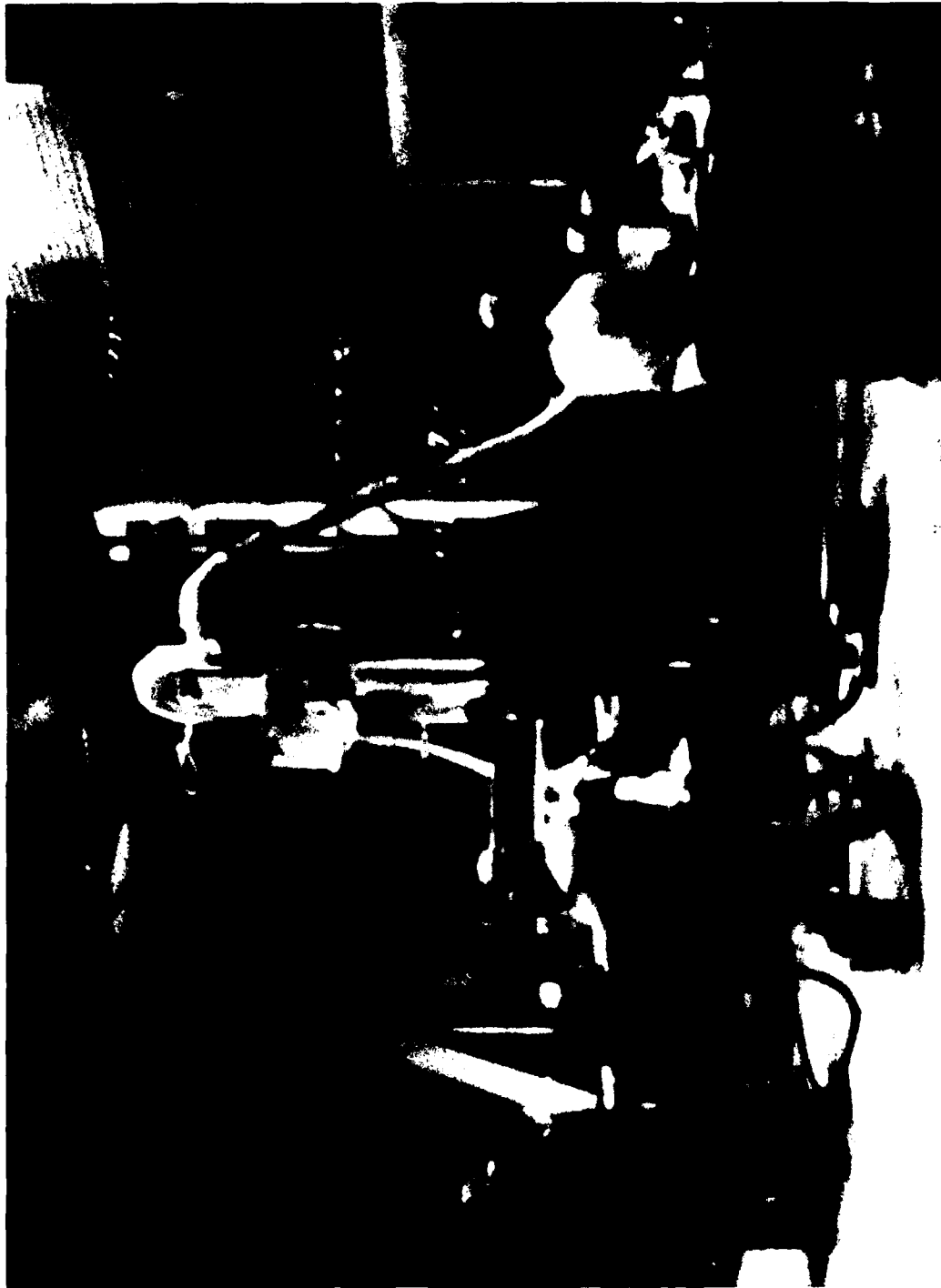


Figure 8. Overall view of Selectrotech's ESC Facility

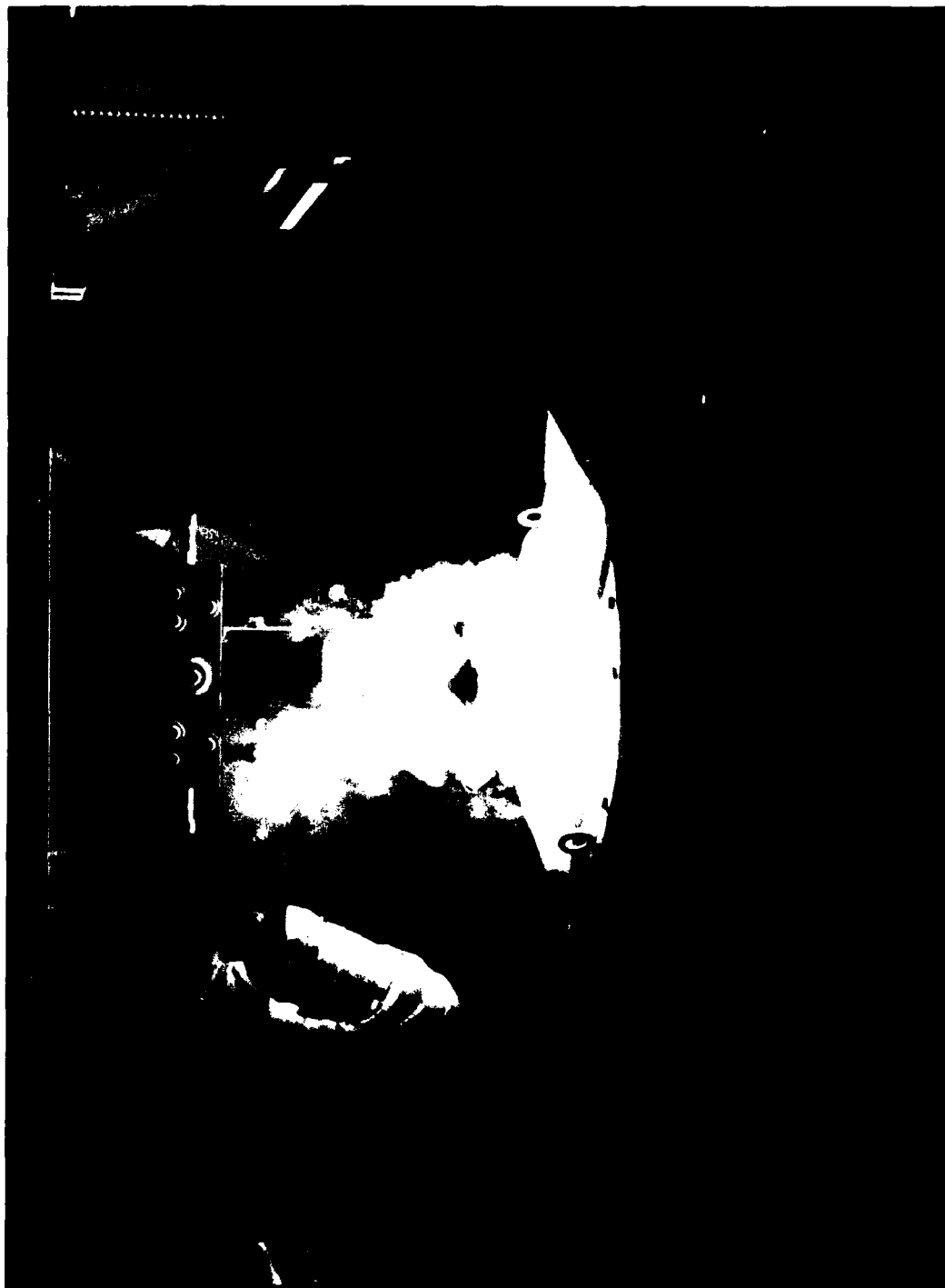


Figure 9. Close-up view of casting in process  
at Selectrotech's ESC Facility.



Figure 10. Overall view of Oregon Graduate Center's ESR melting system (Courtesy of Oregon Graduate Center).



## ELECTROSLAG CAST THIN-WALL HOLLOW CYLINDERS

by R. K. Buhr & Germain Morin

Canada Center for Mineral & Energy Technology

### ABSTRACT

The Canada Centre for Mineral and Energy Technology (CANMET) has been involved with electroslag casting for the past 4 years. Recently this equipment has been modified to produce thin-wall hollow cylindrical castings to almost any desired composition. This report describes the equipment in use and provides information regarding operating parameters and techniques to produce these castings. One of these castings was sectioned extensively and analysed to indicate the degree of homogeneity obtained in the process.



## ELECTROSLAG CAST THIN-WALL HOLLOW CYLINDERS

by R.K. Buhr & Germain Morin

### Introduction

CANMET has been involved with ESC for the past four years. Recently we have modified our ESC equipment to allow us to produce thin-wall hollow cylinders to almost any composition. The following describes the equipment and shows some data on the composition of a steel cylinder produced to a special composition for the Canadian Defense Department.

### Original Equipment

The original concept for the production of these hollow castings involved a movable outer mould coupled to an inner mandrel, both of which were water cooled. Four electrodes were used, each powered by a separate 1000 Amp single phase AC transformer, and were given a reciprocating action to ensure a more uniform distribution of the molten metal in the annulus area. The electrodes were welding wire fed by a variable speed feeder into refractory-coated consumable guide tubes. Electrical connections were made directly to the guide tubes. The outer mould and the mandrel were connected to a load cell and a swivel, which in turn were connected to a screw jack operated by a variable speed motor to permit extraction at various speeds, but at the same time reciprocating. The extraction rate was regulated by the load cell loading, i.e. at a rate to maintain a given load on the extraction mechanism.



### Initial Trials

In the initial trials, we used a cold start technique. This involved a compact of fluorospar and electrolytic iron chips placed beneath each electrode on top of a starting block. As soon as one electrode was started and stabilized, the next was started, until all four were operational. Dry powdered slag was then added to the annulus area until the required amount of molten slag had been obtained. Conditions during the casting period were:

Voltage	25 V
Amperage	600 A
Wire Feed Rate	80 in/min
Casting Speed	1 lb/min
Extraction Rate	5 mm/min
Extraction Load	150 kg
Slag	40% $\text{CaF}_2$ , 30% $\text{Al}_2\text{O}_3$ , 30% $\text{CaO}$

Slide 1 is a photograph of the hollow cylinder produced under these conditions showing the casting, base plate, outer mould, guide tubes, etc. The surface finish of this casting was not good. There were numerous laps and cold shuts on both the inner and outer surfaces, indicating too rapid a solidification rate. These initial trials showed up certain limitations of the process. The solidification rate was too fast. The technique is limited to those compositions available to wire form. Also, weight would be limited by the weight of wire which could be conveniently stored on the spools.

A series of tests were performed to determine the actual temperatures in the mandrel, along with water flow rates and temperatures. Once this was established, it was necessary to assess whether the cooling rate could be sufficiently reduced by throttling the water flow. Naturally, there are severe limitations to this if we want to ensure non-boiling conditions in the cooling channels. We found we could control the outlet water temperature to a maximum of 35°C, and this proved to be beneficial insofar as surface finish was concerned.

A variety of approaches were considered to overcome the compositional limitations imposed by the use of wire electrodes. Concasting of  $\frac{1}{2}$ -inch diameter rod to the required composition was one possibility. Hot swaging and drawing to smaller diameters was also considered, but discarded when some of the more brittle alloys were involved. Steel encased metal powders were thought to be too expensive a solution. Eventually, we decided to employ a version of the Japanese YOZO process coupled with a cast extension of a predetermined composition welded onto the guide tube. This would result in a more massive electrode which would create a larger pool of molten metal to draw upon to produce the thin-wall desired. It would also permit a larger slag volume to be used, increasing the refining characteristics. It also eliminated the need for the reciprocating action to obtain uniform mixing in the annulus area, thus simplifying the setup. The critical factor is still the load to initiate mould movement, and to control the load to ensure no runouts. It turned out that the loads were lower than for the previous setup, being of the order of 90 to 125Kg.

### Final Equipment Description

Slide 2 shows one electrode with case extensions welded onto the guide tube. Slide 3 is a schematic of a complete setup showing all the various bits of equipment involved. Slide 4 is a close up of the electrode assembly prior to start up. As can be seen, we are dealing with relatively close quarters. I should point out that we have used cast aluminum moulds in all our work at CANMET. Although its conductivity is less than copper, aluminum mould costs are significantly less, especially when cooling channels are cast in the aluminum moulds. Slide 5 is a cross section through one of the moulds showing the cooling channel. I believe you would agree that machining such a cooling channel would be expensive. The rounded corners also assist in promoting non-turbulent flow, and thus improves the cooling efficiency.

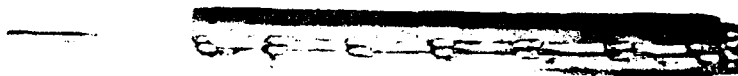
Using this technique, we have produced hollow cylinders to a specific composition for the Canadian Defense Department. This is a high fragmentation type alloy, and is, of course, quite brittle by nature. It could not be made in wire form. A photograph of part of one casting is shown in slide 6. The O.D. is 6 in and the I.D. is 4 in. The surface finish is quite acceptable. Although it can't be seen here, the inside surface is also quite good. We cut a cross section from a cylinder and deep etched it in hot 1:1 HCl. Slide 7 shows this deep etch. The circular patterns coincide with the locations of the guide tubes. This suggested compositional non-uniformity, and so a series of samples were cut from the cylinder and analyzed on a spectrograph. Slide 8 shows the location of these samples and their relation to the guide tubes. The table at the left of the slide indicates the analyses obtained along with the composition of the wire and cast extensions. I believe you will agree there is little evidence of

segregation of any of these elements. Thus, the reason for the etch patterns noted has not been resolved.

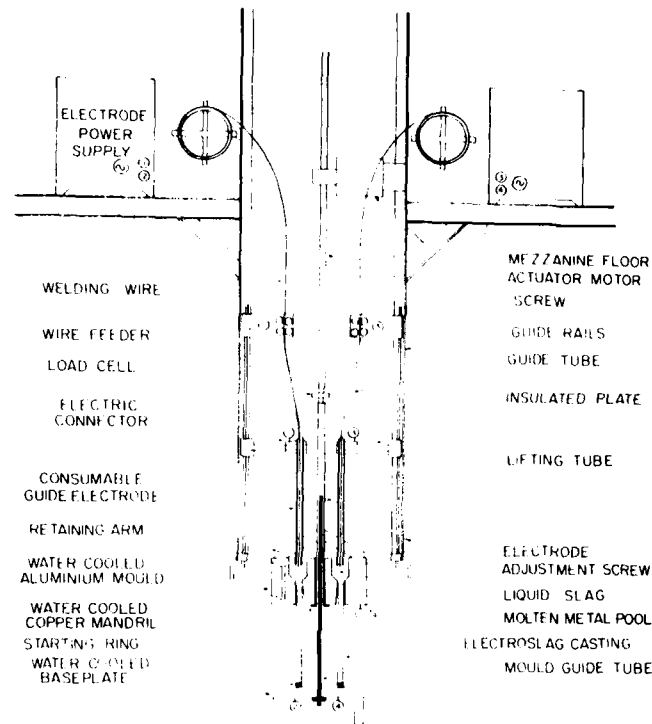
The consistency of analyses indicates this technique to be applicable for the production of a wide range of alloys. Naturally, this technique would not likely be used for commonly produced compositions, but would be of interest in producing some of the more exotic alloys for special applications which cannot be readily fabricated into tubular shapes. We have not tried to make such alloys as yet, but will be making such tests in the near future. However, we now have a process and equipment capable of producing such alloys coupled with the usual refining benefits of electroslog casting.



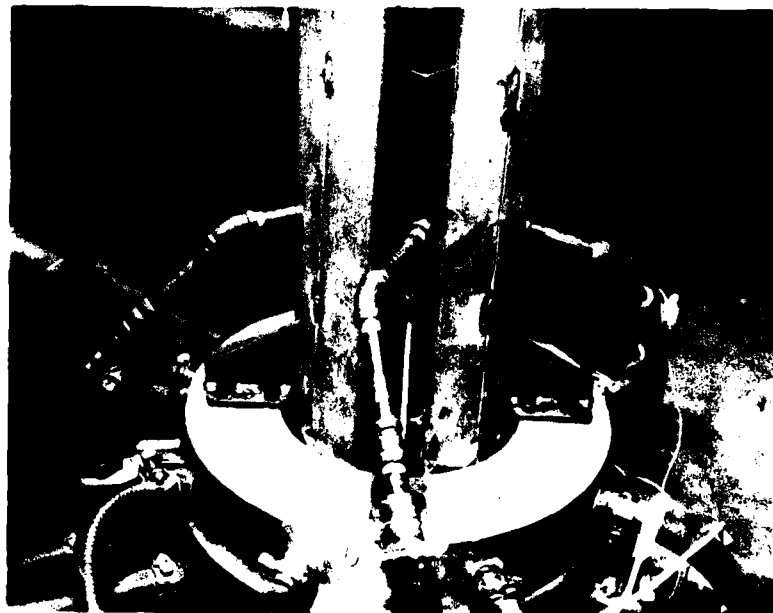
Slide 1. Photograph of ESC equipment used for the production of thin-wall hollow cylinders. Photo shows the casting, base plate, outer mould & refractory coated guide tubes.



Slide 2. Photograph of electrode with cast extensions welded onto the guide tube.



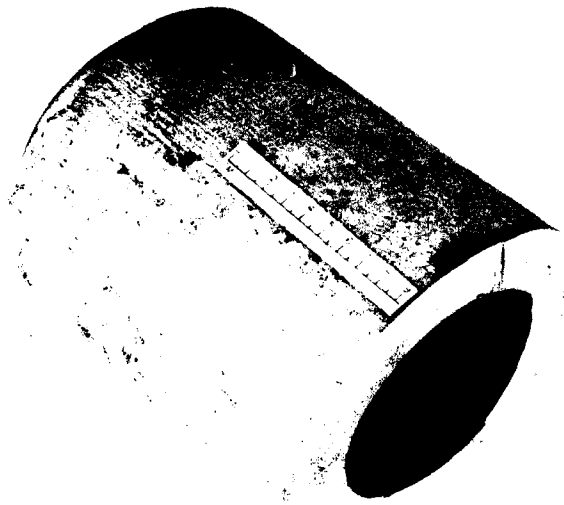
Slide 3. Schematic drawing of ESC equipment after modification to permit the production of thin-wall hollow cylinders to any composition.



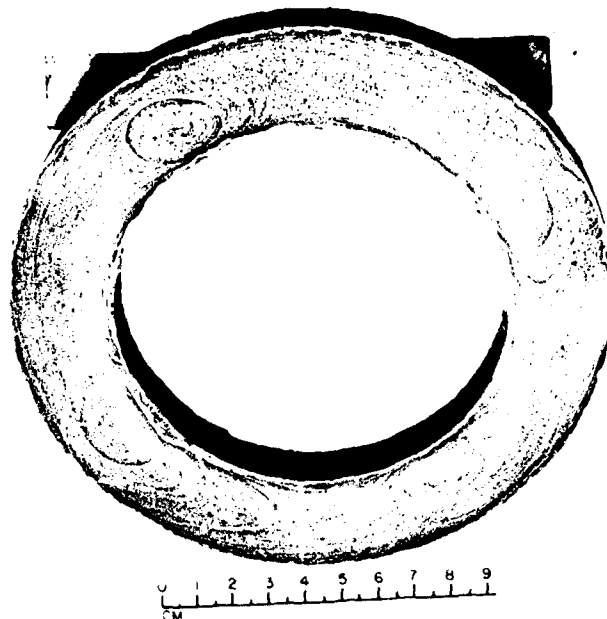
Slide 4. Close up photograph of the electrode assembly prior to melting.



Slide 5. Cross section through the cooling channel in an aluminum ESC mould.



Slide 6. Photograph of a portion of a thin-wall hollow cylinder produced by ESC.



Slide 7. Photograph of a deep etched section taken from the cylinder shown in slide 6.



	ELEMENT %				
	C	Mn	P	Si	S
1E	2.41	2.44	0.07	2.25	0.006
2E	2.41	2.44	0.07	2.25	0.006
3E	2.41	2.44	0.07	2.25	0.006
4E	2.41	2.44	0.07	2.25	0.006
5E	2.41	2.44	0.07	2.25	0.006
6E	2.41	2.44	0.07	2.25	0.006
7E	2.41	2.44	0.07	2.25	0.006
8E	2.41	2.44	0.07	2.25	0.006
9E	2.41	2.44	0.07	2.25	0.006
10E	2.41	2.44	0.07	2.25	0.006
11E	2.41	2.44	0.07	2.25	0.006
12E	2.41	2.44	0.07	2.25	0.006
13E	2.41	2.44	0.07	2.25	0.006
14E	2.41	2.44	0.07	2.25	0.006
15E	2.41	2.44	0.07	2.25	0.006
16E	2.41	2.44	0.07	2.25	0.006
17E	2.41	2.44	0.07	2.25	0.006
18E	2.41	2.44	0.07	2.25	0.006
19E	2.41	2.44	0.07	2.25	0.006
20E	2.41	2.44	0.07	2.25	0.006
21E	2.41	2.44	0.07	2.25	0.006
22E	2.41	2.44	0.07	2.25	0.006
23E	2.41	2.44	0.07	2.25	0.006
24E	2.41	2.44	0.07	2.25	0.006
25E	2.41	2.44	0.07	2.25	0.006
26E	2.41	2.44	0.07	2.25	0.006
27E	2.41	2.44	0.07	2.25	0.006
28E	2.41	2.44	0.07	2.25	0.006
29E	2.41	2.44	0.07	2.25	0.006
30E	2.41	2.44	0.07	2.25	0.006
31E	2.41	2.44	0.07	2.25	0.006
32E	2.41	2.44	0.07	2.25	0.006
33E	2.41	2.44	0.07	2.25	0.006
34E	2.41	2.44	0.07	2.25	0.006
35E	2.41	2.44	0.07	2.25	0.006
36E	2.41	2.44	0.07	2.25	0.006
37E	2.41	2.44	0.07	2.25	0.006
38E	2.41	2.44	0.07	2.25	0.006
39E	2.41	2.44	0.07	2.25	0.006
40E	2.41	2.44	0.07	2.25	0.006
41E	2.41	2.44	0.07	2.25	0.006
42E	2.41	2.44	0.07	2.25	0.006
43E	2.41	2.44	0.07	2.25	0.006
44E	2.41	2.44	0.07	2.25	0.006
45E	2.41	2.44	0.07	2.25	0.006
46E	2.41	2.44	0.07	2.25	0.006
47E	2.41	2.44	0.07	2.25	0.006
48E	2.41	2.44	0.07	2.25	0.006
49E	2.41	2.44	0.07	2.25	0.006
50E	2.41	2.44	0.07	2.25	0.006
51E	2.41	2.44	0.07	2.25	0.006
52E	2.41	2.44	0.07	2.25	0.006
53E	2.41	2.44	0.07	2.25	0.006
54E	2.41	2.44	0.07	2.25	0.006
55E	2.41	2.44	0.07	2.25	0.006
56E	2.41	2.44	0.07	2.25	0.006
57E	2.41	2.44	0.07	2.25	0.006
58E	2.41	2.44	0.07	2.25	0.006
59E	2.41	2.44	0.07	2.25	0.006
60E	2.41	2.44	0.07	2.25	0.006
61E	2.41	2.44	0.07	2.25	0.006
62E	2.41	2.44	0.07	2.25	0.006
63E	2.41	2.44	0.07	2.25	0.006
64E	2.41	2.44	0.07	2.25	0.006
65E	2.41	2.44	0.07	2.25	0.006
66E	2.41	2.44	0.07	2.25	0.006
67E	2.41	2.44	0.07	2.25	0.006
68E	2.41	2.44	0.07	2.25	0.006
69E	2.41	2.44	0.07	2.25	0.006
70E	2.41	2.44	0.07	2.25	0.006
71E	2.41	2.44	0.07	2.25	0.006
72E	2.41	2.44	0.07	2.25	0.006
73E	2.41	2.44	0.07	2.25	0.006
74E	2.41	2.44	0.07	2.25	0.006
75E	2.41	2.44	0.07	2.25	0.006
76E	2.41	2.44	0.07	2.25	0.006
77E	2.41	2.44	0.07	2.25	0.006
78E	2.41	2.44	0.07	2.25	0.006
79E	2.41	2.44	0.07	2.25	0.006
80E	2.41	2.44	0.07	2.25	0.006
81E	2.41	2.44	0.07	2.25	0.006
82E	2.41	2.44	0.07	2.25	0.006
83E	2.41	2.44	0.07	2.25	0.006
84E	2.41	2.44	0.07	2.25	0.006
85E	2.41	2.44	0.07	2.25	0.006
86E	2.41	2.44	0.07	2.25	0.006
87E	2.41	2.44	0.07	2.25	0.006
88E	2.41	2.44	0.07	2.25	0.006
89E	2.41	2.44	0.07	2.25	0.006
90E	2.41	2.44	0.07	2.25	0.006
91E	2.41	2.44	0.07	2.25	0.006
92E	2.41	2.44	0.07	2.25	0.006
93E	2.41	2.44	0.07	2.25	0.006
94E	2.41	2.44	0.07	2.25	0.006
95E	2.41	2.44	0.07	2.25	0.006
96E	2.41	2.44	0.07	2.25	0.006
97E	2.41	2.44	0.07	2.25	0.006
98E	2.41	2.44	0.07	2.25	0.006
99E	2.41	2.44	0.07	2.25	0.006
100E	2.41	2.44	0.07	2.25	0.006
WIRE	0.18	1.19	0.010	0.60	0.020
CAST BAR	2.70	3.50	0.025	2.58	0.030

Slide 8. Schematic of ESC cylinder and the location of samples and their analyses.





## **ELECTROSLAG NET SHAPES OF FERROUS AND NON-FERROUS ALLOYS**

**G. K. Bhat**  
**Bhat Technology International, Inc.**

Electroslag casting (ESC) is a variation of the well known electroslag remelting process which offers direct - short cut route for the manufacture of near net shaped components of a wide range of alloy materials. Special advantages offered by the electroslag casting process include: refining of metal with molten slag, exclusion of liquid metal contact with air, the use of cooled metal molds instead of sand or refractories, progressive formation of cast shape from a small volume of molten metal, possibility of treatment of the metal with reactive gas, deoxidation, removal of solid inclusions, and gases form the molten metal so as to produce solidified metal of the high quality, oriented structure and controlled grain size.

The production of near net shapes contributes significantly to the reduction of material wastage, machining requirements and labor savings. Compared to the capital investment required to establish an alloy steel foundry or a forging shop, the electroslag casting plant will require much less capital investment

Since the components produced by electroslag castings are not inferior to forgings of same alloys, the ESC process deserves attention by the research and industrial community.

The electroslag remelting (ESR) process has been favorably accepted by metals industries throughout the industrialized world. The ESR process has survived despite a quarter century period of neglect by the U.S. industry since 1939, when the first U.S. patent for the process was issued to Hopkins. The growth of the ESR process in the U.S. since 1956 was phenomenal.

It is unfortunate that despite more than 15 years of ESR materials production and applications in the U.S., code approval of specifications for electroslag remelted materials has proceeded very slowly. Consequently, the usage of ESR materials is still restricted. The producer and user have been unable to obtain the full benefits of their resources invested in this technology.

The advent of directly manufacturing complex shaped components by the electroslag casting process has now offered to the machinery and systems building companies new capabilities and significant competitive advantages.

Electroslag casting (ESC) manufacturing process is of special importance to the builders of various machinery systems. Electroslag casting process can be advantageously applied in the following cases: (1) when it is difficult and expensive to produce cast components in small lots, and within short lead times by alternate manufacturing techniques; (2) when the production of a cast component is labor intensive; (3) when high quality casting of a hard to deform alloy has to be made; (4) when it is required to produce a net shaped or near net shaped casting of a high integrity and service performance characteristics without forging, excessive machining, wastage of metal and energy (5) when it is required to consistently meet specification, reduce variations in chemical compositions, minimize both the size and volume of inclusions, obtain narrow band mechanical properties and predict useful service life with reasonable accuracy. Electroslag casting minimizes or eliminates the need for weld fabrication of components, reduces quality assurance work load.

Conventional steel casting process is normally considered highly cost-effective provided that a large number of the same component is repetitively produced in an assembly line fashion. Normal foundry processing has many cost intensive preliminary steps and, therefore, large quantity castings order is required to amortize the initial set-up costs.

Machinery systems component orders, for the most part, may be considered as small lot orders requiring special handling. In such cases, forged components are fair replacements to cast components, but the production of complex shaped components is expensive. Forging requires huge capital investment in plant equipment and machining facilities. Excessive loss of metal as chips, flashings and grinding dust and their disposal add significant costs.

Components made through the electroslag casting process are viable alternatives for conventional castings and forgings. Electroslag casting technology has provided a fundamentally new method of improving the physical and mechanical properties and, consequently, the service performance characteristics of cast components. In fact, forged component properties are easily attained and even augmented in electroslag castings. Since cast components tend to exhibit better corrosion properties than their forged counterparts, it can be safely said the electroslag cast components provide both improved mechanical properties and corrosion resistance.

The electroslag casting process (ESC) neatly integrates into a single manufacturing operation, the individual processes of alloy melting, melt purification, production of cast shapes requiring external attachments and internal cavity, uniform

chemical composition and mechanical properties which are equivalent and even superior to those produced by other manufacturing processes. Bonus features of the ESC process include savings in labor, total energy, investment in heavy forging presses, or foundry, machine shop, elaborate in-process controls and inspection costs.

In the USSR, Japan, Scandinavia, Eastern Europe, and recently in Canada, the use of electroslag cast components for critical applications in the chemical, nuclear, power generation, marine and machine building industries has steadily increased to a point that special electroslag casting shops have been built to serve these captive customers. Users of this concept have claimed that end item costs have been significantly reduced, it has conserved materials, reduced procurement lead times and eliminated the need for warehousing and financing large inventories of forged and machined components.

ESC components without welds and transitional structure zones adjacent to the welds provide for better corrosion resistance and thereby augment service life of systems and reduce their maintenance costs.

ESC components offer attractive potential for substitution of expensive forged components, especially of high alloy materials which are hard to deform or which cannot be easily welded.

The aforementioned factors clearly emphasize the need for further studies and support of this technology by the industrial and government sectors in the U.S.

## EXAMPLES OF ELECTROSLAG PRODUCTS

### A. ESC Components for Chemical and Petrochemical Industries

1. Cup shaped end segments of high pressure vessels.
2. Pressure vessels by joining two ESC segments.
3. Pipe billets ( diameters up to 600 mm and 3.5 - 4.0 meters long)
4. Pipe billets with axial and non-axial cavities of different geometries.
5. Fluted pipe billets with external slots, ribs, and built-up surfaces.
6. Stop valve bodies for steam and nuclear power plants (up to 500 mm dia.) and 4 tons in weight)
7. Well drilling hardware (cutters, non-corrosive material tubular items)

### B. ESC Componentets for Metallurgical Industries

1. Die blanks
2. Pipe rolling grooved rolls
3. Rolling mill rolls
4. Billet piercing mandrels
5. Composite rolls
6. Support rails, box beams for high temperature heating furnaces.

C. Ship Building Industry

1. Mechanical pipes, tubes, and elbows
2. Marine Engine shafts, piston rods, piston heads, and crank shafts

D. Machine Building Industry

1. Machine frames
2. Eccentric shafts for stamping and forging presses
3. Gear rings of special profile

E. Tractor Parts

1. Gear wheels
2. Rings, shafts, spindles

F. Cement Industry

1. Cement kiln bands of special shapes.

G. High Pressure Vessel Bodies

1. Steam Boilers ( up to 2.5 meters in diameter)
2. Nuclear reactor pump and pressure vessel housing (up to 150 to 350 mm wall thickness)
3. Hydrocracking reactors

## EXAMPLES OF ELECTROSLAG NET SHAPE MANUFACTURING PROCESS

### A. Permanent mold electroslag net shapes

Consumable electrode is remelted in a ceramic crucible. Remelting is done in an electroconductive refining slag. Refined molten metal is poured into a steel, ceramic or cast iron mold depending upon the alloy composition and its reactivity with mold material. Small complex shaped net shaped components can be produced using simple, low-investment process equipment as shown in Figures 1(a) and 1(b). Molten metal is prepared using consumable electrode of required alloy composition as shown in figure 1(a). Figure 1(b) shows the use of non-consumable electrode and scrap and/or alloy ingredient charge for the preparation of molten metal. The slag acts as a protective medium for the molten metal and as a protective layer for the mold surface.

### B. Electroslag net shapes production using vertical and horizontal centrifugal casting machines.

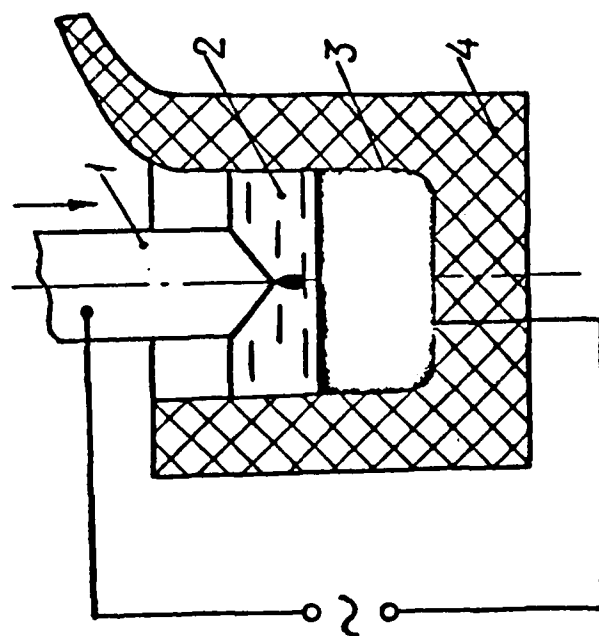
Molten metal is prepared in ceramic crucible as in A. The molten metal is poured as shown in Figure 2(a) into a vertical centrifugal caster and in a horizontal centrifugal caster as in Figure 2(b).

Figure 1 - Molten metal preparation schematic

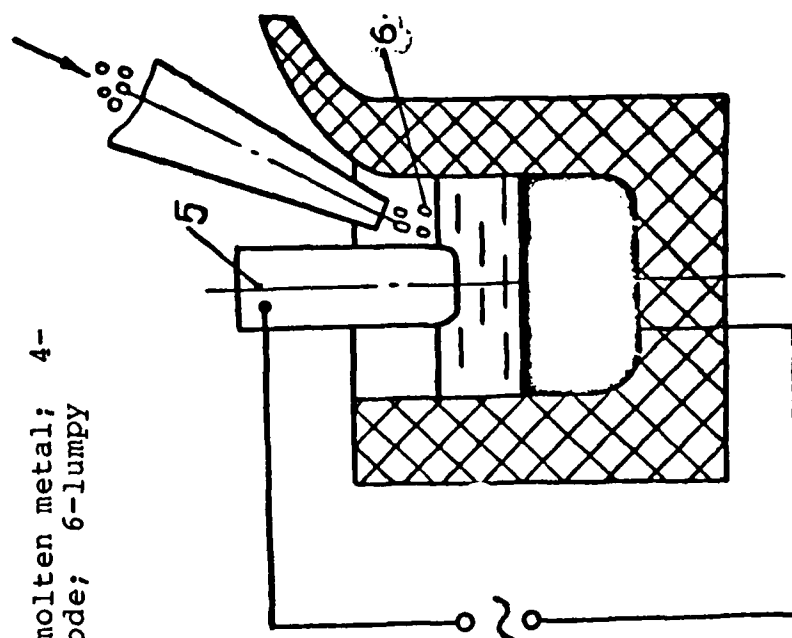
(a) Electroslag remelting of consumable electrode in a ceramic crucible.

(b) Melting lumpy charge using a non-consumable electrode for heating molten slag.

1- consumable electrode; 2- molten slag; 3- molten metal; 4- melting crucible 5- non-consumable electrode; 6- lumpy charge or scrap



a.



b



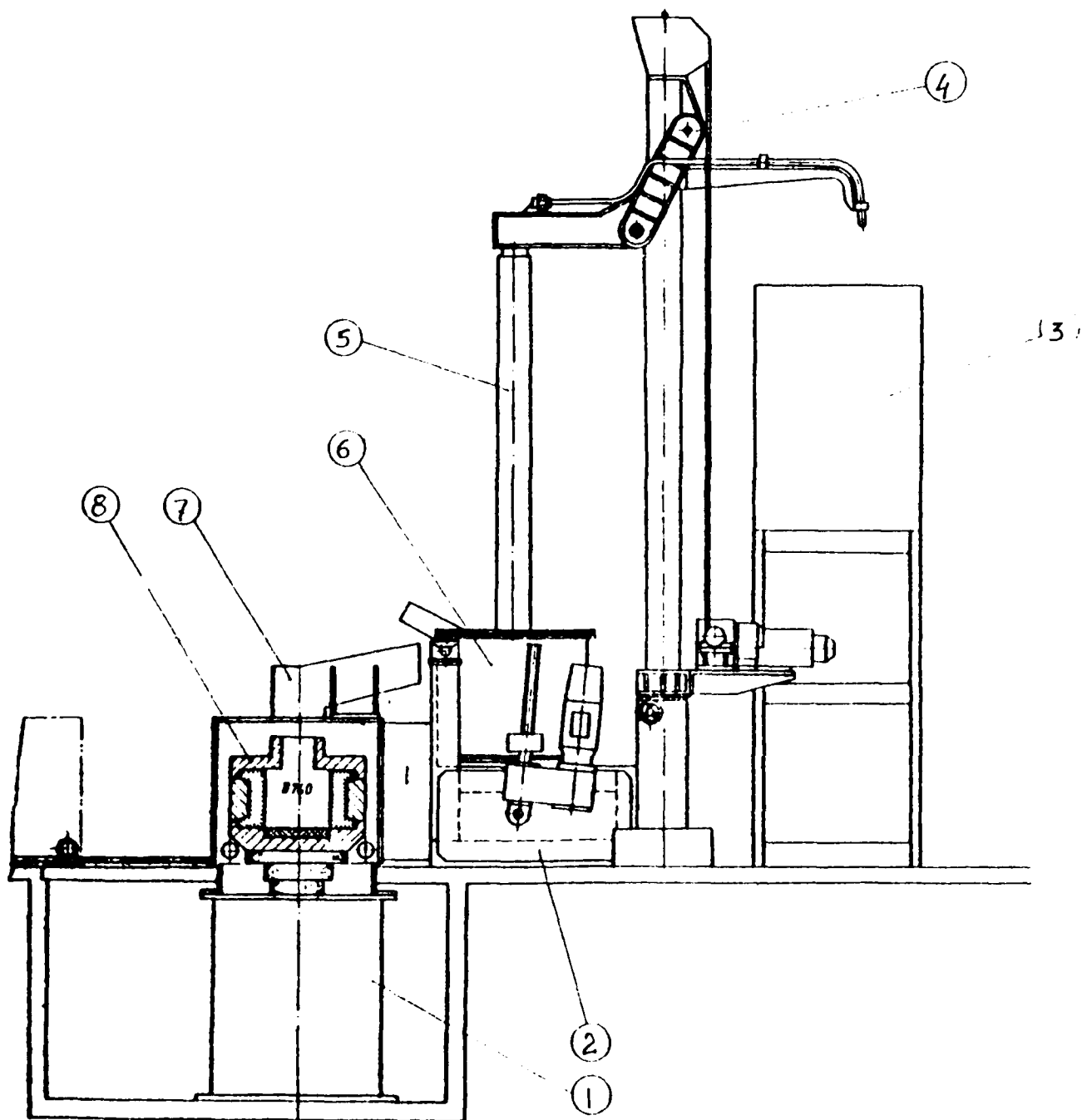
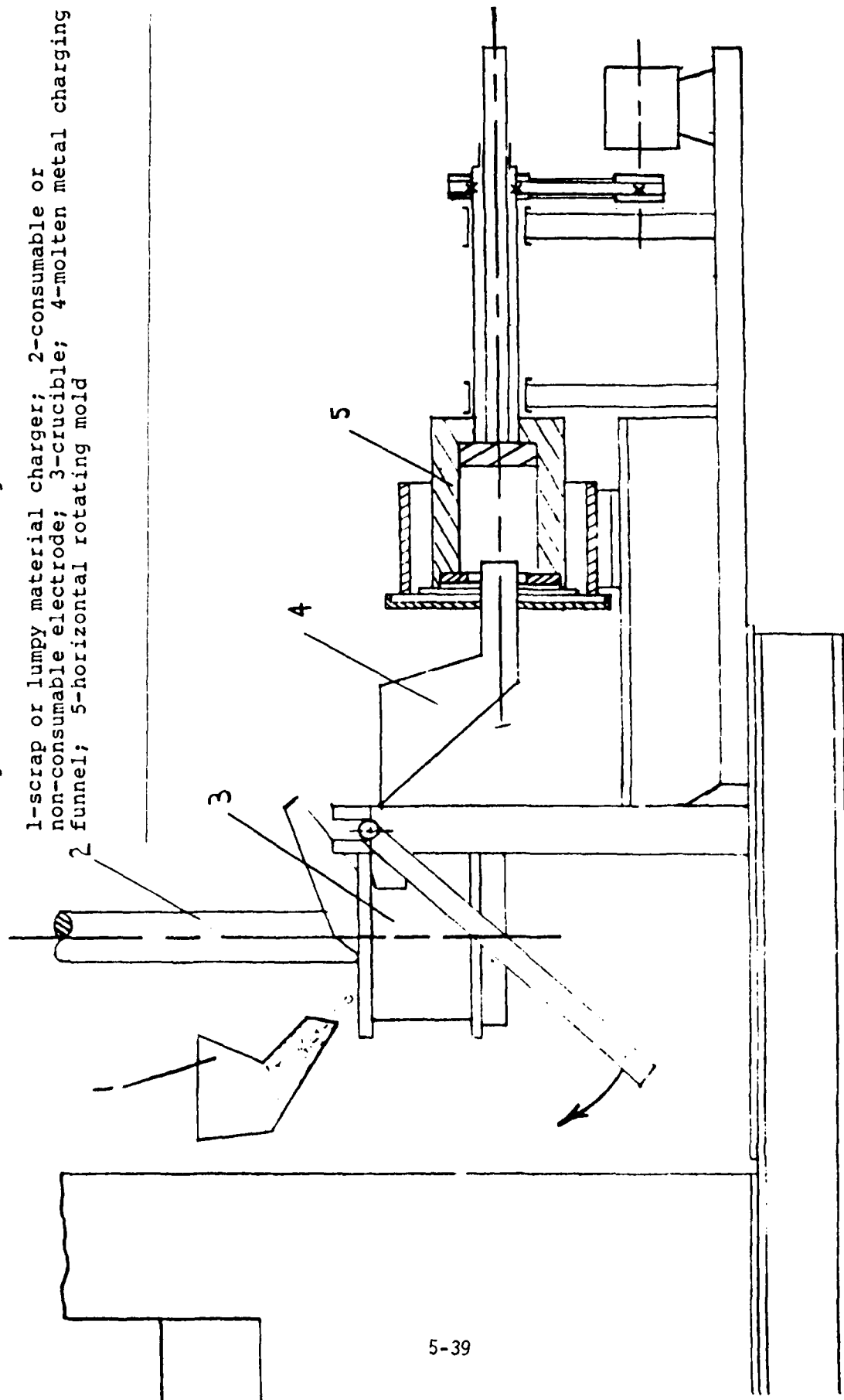


Figure 2(a) - Schematic of Electroslag net shape production in rotating mold

(a) Vertical centrifugal caster

1-centrifugal caster; 2-tilter; 3-power source; 4-electrode feeder; 5-consumable electrode; 6-melting crucible; 7-pouring cup; 8-shaping mold.

Figure 2(b) Schematic of electroslag net shape production using a horizontal rotating mold.



SUMMARY OF  
WORKING GROUP REPORTS  
ON  
ELECTROSLAG PROCESSING  
FOR  
MARINE APPLICATIONS

## WORKING GROUP A - ELECTROSLAG WELDING OF FERROUS ALLOYS

Presenters: Dr. A. W. Pense and Dr. D. F. Hasson -

Lehigh University and United States Naval Academy

### I. POTENTIAL PAYOFF AND FUTURE USE IN MARINE APPLICATIONS

#### A. Ship Hulls and Components

While electroslag welding will continue to be used for fabricating commercial and some military ship secondary structural and machinery components, it will not be extended much beyond its present use. Some ship components, such as machinery bases, rigging, and support equipment (lugs, cylinders) do represent a possible growth area.

B. Specialty items such as shaft liners (with stainless) and inserts of gradually changing composition (carbon to stainless joints) also represent potential applications, but are within the current technology capability.

C. Offshore structures, particularly thick tubular structures, represent a potential market, but significant limitations must be overcome.

D. Castings for shipboard use made by the electroslag casting method represent a good potential market in the light of current casting quality.

### II. LIMITATIONS PREVENTING APPLICATION

A. Primary limitation to extension of electroslag welding to more ships and to tubular structures is the achievable HAZ toughness. The

higher strength, higher toughness steels, such as used in North Sea platforms and now being developed for ships, depend on heat treatment for development of optimum strength and toughness. Because of resulting HAZ low toughness, these steels are at present too sensitive to use electroslag welding. New microalloyed hull steels are being developed that may possess acceptable high heat input HAZ toughness values for some applications.

B. Process control needs to be addressed by a systems approach when using electroslag welding. Rather than trying to optimize each step in the welding process, the overall process needs to be optimized. Electroslag welding needs good fitup, so overall savings only come when careful preparation precedes welding and good operational procedures are followed. This is true of any automatic welding but especially true of electroslag.

C. Consumables (wires and fluxes) for higher strength steels need to be developed and expanded.

D. Some of the newer ideas, such as shaft overlays and gradual transition pieces, need to be applied in a planned and systematic way so some experience with their characteristics can be obtained.

### III. PROPOSED SOLUTIONS TO LIMITATIONS

A. More suppliers (hopefully domestic) need to provide new microalloyed steels tailored to give good HAZ toughness in high heat input welding.

B. Consumables to match higher strength, high toughness plates need to be developed ( $> 65\text{-}70$  ksi yield strength).

C. Methods for quantitative cost assessment which incorporate a systems approach to weld design and fabrication need to be developed and promoted so automatic processes like electroslog welding can be better utilized.



## WORKING GROUP B - ELECTROSLAG WELDING OF NONFERROUS ALLOYS

Presenter: Dr. Robert Frost - Colorado School of Mines

Group B addressed first, applicable nonferrous alloy systems for electroslag welding. The group concluded that there appeared to be more payoff for this welding method in the nonferrous alloy systems than for the ferrous alloys. The reason for this being the potential for fewer heat-affected zone problems in the nonferrous alloy systems.

The group identified the following alloy systems as being particularly suitable for electroslag welding:

1. Aluminum and copper base alloys used for electrical (busbar) applications.
2. Monel and Inconel alloys for seawater corrosion resistance and high temperature cladding.
3. Copper-nickel alloys
4. Titanium alloys

The most obvious application appeared to be thick-cladding of components. In this regard, priorities for development are:

1. Consumables

Fluxes and alloys suitable for electroslag welding need to be developed and made commercially available.



## 2. Nondestructive Testing

The potential of large grain size commonly developed in these alloys needs to be addressed to make NDE less difficult.

Residual stresses developed by this process should also be examined.

## 3. In-Process Control Contamination

In many of these alloys, the environment can detrimentally affect the properties of the electrosag weld by supplying nitrogen, hydrogen and oxygen to the alloy. For alloys of titanium, this is especially true and careful shielding of the process is necessary. Process development to control these levels for sensitive alloy systems is necessary.

An additional concern is for disposal of the toxic products of electrosag welding. Of particular concern are the resulting toxic gaseous fumes and the other toxic flux by-products. Before this technology sees widespread industrial application, this area will need to be addressed.

Future application of electrosag processing for marine application will depend on resolution of those problems and more importantly the identification of its cost benefits in comparison to currently available welding processes.

### WORKING GROUP C - ELECTROSLAG CASTING

Presenter: Mr. William Palko - David Taylor Naval Ship R&D Center

Electroslag casting appears to be a promising processing method for marine applications. This group noted a number of applications, some of which included pipe fittings, condenser heads, valve bodies, and hull penetration castings.

The benefits of using electroslag casting over conventional sand castings are reduced casting defects, a potential for improved properties and a potential to control grain size.

The benefit of reducing casting defects and controlling grain size could have significant impact on nondestructive testing. Likewise, less rework to achieve an acceptable casting could be a notable impact on the cost of hard-to-cast alloys.

Improved properties of ferrous electroslag castings were identified in this workshop. If properties of electroslag castings in other ferrous and nonferrous alloys can continue to approach minimum forging properties, then this technology could find greater acceptance. The development of effective methods to control grain size in the electroslag process appears feasible and could provide, at least in part, further improvement in the electroslag casting's mechanical properties.

Limitations of the electroslag casting process are not well defined because of the limited application of this process domestically. Power necessary to melt large electrodes may not be available to certain sources but this is not a technological limit.

Costs for electroslag castings are difficult to project because the process is in its infancy in regards to its commercial application. The cost factor will be crucial in determining the extent to which electroslag casting will be commercially developed. A current process limitation for electroslag casting is the potentially high hydrogen level in the cast product. Alloys which cannot tolerate hydrogen greater than 3 parts per million would require further process controls to be developed before electroslag casting could be a viable means of producing these alloys.

In the near-term, further characterization of electroslag cast alloys needs to be accomplished to demonstrate the mechanical property advantages. With the increasing number of sources for electroslag casting, the potential for developing this technology for marine application looks encouraging.

APPENDIX A

WORKSHOP PARTICIPANTS

### Workshop Attendees

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APPENDIX B

WORKSHOP AGENDA



## AGENDA

### ELECTROSLAG PROCESSING FOR MARINE APPLICATIONS WORKSHOP

United States Naval Academy  
Rickover Hall  
Annapolis, Maryland

Tuesday, 5 March 1985

- 0800 - Assembly/Registration  
(Rickover Hall, Room 103)
- 0830-0845 - Introduction - Mr. C. A. Zanis (Naval Sea Systems Command)
- SESSION I - Electroslag Welding of Ferrous Alloys  
Chairman - Dr. Dennis F. Hasson (United States Naval Academy)
- 0845-0925 - Status of Electroslag Welding Process Technology  
Presenter: Dr. R. H. Frost (Colorado School of Mines)
- 0925-1005 - Concerns in Electroslag Welding Ferrous Alloys  
Presenter: Dr. George Reynolds (MSNW, Inc.)
- 1005-1020 - Coffee Break
- SESSION II - Electroslag Welding of Nonferrous Alloys/Electroslag Casting  
Chairman - Dr. Dennis F. Hasson
- 1020-1100 - Concerns in Electroslag Welding Nonferrous Alloys  
Presenter: Dr. Jack Devletian (Oregon Graduate Center)
- 1100-1140 - Status of Electroslag Casting Technology  
Presenter: Dr. R. R. Judkins (Oak Ridge National Laboratories)
- 1140-1300 - Lunch - Naval Academy Officer's Club
- SESSION III - Applications and Trends in Electroslag Welding  
Chairman - Mr. Ivan Caplan (DTNSRDC)
- 1300-1320 - United States  
Dr. B. Howser (MARAD SP7/B)
- 1320-1340 - Western Europe  
Dr. P. Threadgill (The Welding Institute)
- 1340-1400 - Canada  
Mr. B. A. Graville (Submitted Manuscript)
- 1400-1420 - Japan  
Dr. T. Eager (Naval Research Office, Tokyo)  
Presented by Dr. D. F. Hasson

- 1420-1440 - Union of Soviet Socialist Republics/Eastern Europe  
Dr. V. Malin (GARD, Inc.)
- 1440-1500 - Comments and Discussion  
Leader: Dr. D. F. Hasson (U. S. Naval Academy)

Wednesday, 6 March 1985

SESSION IV - Applications and Trends in Electroslag Casting  
Chairman - Mr. William Palko (DTNSRDC)

- 0815-0845 - Domestic  
Mr. M. Hobday (Department of Energy) and
- 0845-0915 - Foreign  
Dr. K. Bhat (Selectro Tech, Inc.)
- 0915-0930 - Comments and Discussion  
Leader: Mr. W. A. Palko (David Taylor Naval Ship  
Research and Development Center)
- 0800 - 0815 - Assembly  
(Rickover Hall, Room 103)
- 0930-1030 - Definition of Technical Requirements \*\*

Working Group A - Electroslag Welding of Ferrous Alloys (Room 104)

Suggested Discussion Leaders: Dr. A. Pense/Dr. D. Hasson

Working Group B - Electroslag Welding of Nonferrous Alloy  
(Room 108)

Suggested Discussion Leaders: Dr. R. Frost/Mr. I. Caplan

Working Group C - Electroslag Casting

Suggested Discussion Leaders: Dr. V. Shende/Mr. W. A. Palko

- 1100-1200 - Plenary Review and Summary (Room 103)
- 1100-1115 - Working Group A Report - Drs. Pense/Hasson
- 1115-1130 - Working Group B Report - Dr. Frost/Mr. Caplan
- 1130-1145 - Working Group C Report - Dr. Shende/Mr. Palko
- 1145-1200 - Closing Remarks - Mr. C. A. Zanis

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)  This document presents an overview of a one and one-half day, international workshop held at the United States Naval Academy, Annapolis, Maryland. The purpose of the workshop was to review and discuss the status of electroslag processing technology and to identify opportunities and directions for expanded application of electroslag processing technology in marine applications.  A series of presentations were made to review the status of electroslag welding and casting in ferrous and nonferrous alloys. Following this introduction, current applications and trends for this technology were reviewed by the workshop's participants. The final sessions consisted of a series of working group meetings where the key issues and opportunities for expansion of this technology into marine applications were identified.					
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## Block 19. ABSTRACT (Cont)

In general, the workshop participants agreed that electroslog processing is a relatively mature technology which is used extensively in marine applications. Expanded application of this technology may be realized if technical progress is made in the following areas:

- Development of electroslog filler metals and procedures to take advantage of the improvements in high strength low alloy steel processing technology. Microalloyed steels continue to be developed with superior heat affected zone toughness at high heat inputs. Parallel developments in high heat input welding consumables and in-process control techniques should be accelerated.
- The capability to control grain size and attain mechanical properties equivalent to forged products should be developed and demonstrated for electroslog castings. Manufacturing procedures for steel components with acceptable mechanical properties and hydrogen levels should be developed and demonstrated for electroslog castings. Manufacturing procedures for steel components with acceptable mechanical properties and hydrogen levels should be developed. Grain size and impurity level control in non-ferrous alloys, particularly titanium alloys, should be pursued.
- A need, which is more generic than electroslog welding or processing is the requirement for analytical tools to assess costs of alternative manufacturing processes, specifically welding processes. Process selection tradeoffs, such as fit up requirements, consumables, joint preparation, electrical intensity, etc., must be considered in a manageable form so that optimum process/application selections are made.

Details of the technical presentations and the working group recommendations are presented in the following sections of this document

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